

From ocean science to policy-ready services: the European Digital Twin Ocean in practice

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Abstract

Supporting the science-to-policy mandates of the One Ocean Science Congress, this paper demonstrates how the European Digital Twin Ocean (EDITO) transforms trusted ocean models and observations into policy-ready digital services. Through configurable, relocatable, and repeatable workflows, EDITO enables the production of indicators and maps for habitat suitability, optimised ship routing, oil spill and microplastic hazards. These outputs support biodiversity conservation, maritime decarbonisation, pollution management, and emergency response.

Built on the Copernicus Marine Service, EMODnet, and European cloud and high-performance computing resources, EDITO provides a framework for standardised workflows that can be easily reproduced and run on demand. Drawing on six cross-domain applications, we analyse how design choices related to workflow architecture, modularity, user interfaces, and relocatability influence usability and scalability. The results show how FAIR scientific workflows can bridge the gap between ocean science and decision-making by turning validated models into actionable services aligned with policy needs.

Introduction

Following ongoing societal transitions — in domains such as energy, food, nature and transportation — decision-making processes are increasingly shifting towards being more inclusive, integrated, long-term and adaptive ^{1,2}. Digital technologies are evolving to support these growing information needs, notably through the emergence of environmental digital twins. These systems can be understood as an extension of traditional modelling approaches, integrating (real-time) data and simulation capabilities into dynamic, data-driven representations of environmental systems, often coupled with interactive interfaces for exploration and decision support ^{3,4}. Similarly, Digital Twin Oceans (DTOs) are framed as integrated systems that combine ocean observations and models to enable scenario-based, policy-relevant, on-demand decision support across ocean domains ⁵.

In parallel, ocean science has undergone a major transformation in data availability and accessibility through interoperable platforms such as SeaDataNet, PANGAEA, and EMODnet ⁶. While this has enabled significant progress in data integration, ocean models and analytical tools remain comparatively fragmented and difficult to reuse across contexts and institutional boundaries. Extending the FAIR (Findable, Accessible, Interoperable, and Reusable) principles from interoperable data infrastructures ⁷ to computational workflows is therefore a key step towards integrating ocean data, models, and applications into cohesive digital ecosystems. The FAIR principles for computational workflows mean findability through public repositories and registries, ensuring accessibility through easy- or no installation and open licensing, promoting interoperability through standardization and compatibility with other tools and models, and ultimately enabling reusability through versioning and clear documentation of functionality and dependencies ^{8,9}. After completing the first crucial step of moving from fragmented data to interoperable and centralized data systems, the marine science community is transitioning towards integrated digital twins, where both the data and computational workflows are FAIR, as also suggested for the biodiversity domain ¹⁰.

At the same time, ocean forecasting systems are increasingly expected to deliver value beyond scientific outputs, supporting end-user applications in areas such as maritime operations, environmental management, and climate adaptation ¹¹. There is growing demand both within and across domains. This growing demand reinforces the need for application-driven, user-centric services in which data, models, and applications are combined into centralized and standardized systems capable of supporting diverse decision contexts. However, a persistent gap was highlighted ⁵ between technical capability and actionable use, which calls for user-oriented design and outputs aligned with management questions.

We must also recognize that the evolution of environmental information systems into digital twins is closely linked to emerging policy demands for integrated, actionable, and scalable knowledge systems. The current leap for a digital twin of the ocean is therefore strongly aligned with the *United Nations Ocean Decade of Ocean Science for Sustainable Development* (2021–2030) (“Ocean Decade”), which aims to accelerate transformative action towards ocean sustainability across

ecological, social, and economic dimensions. Central to the Ocean Decade is the identification of knowledge needs, the generation of that knowledge, and its effective uptake in decision-making ¹². These priorities are operationalized through a set of Ocean Decade Challenges, including Challenge 8, which explicitly calls for the development of a digital representation of the ocean. This ambition is further articulated in the UN Digital Twins of the Ocean (DITTO) programme, positioning digital twin approaches as a key enabler of the Ocean Decade's objectives.

The European Union has its own initiative to achieve European (and global) policy goals related to our oceans and coasts. This initiative is the EU Digital Twin Ocean (EU DTO), which includes the European Digital Twin Ocean (EDITO) as a core infrastructure platform. EDITO leverages existing European assets (i.e., in situ and satellite monitoring and federated computing infrastructure) and offers data and tools for consistent high-resolution, multi-dimensional descriptions of the ocean ¹³. The European Ocean Pact ¹⁴ makes the operationalization of EDITO by 2030 an explicit target, which shows high level political commitment.

To understand the concept of Digital Twins, six aspects of an information system are defined ¹⁵ that together form a Digital Twin, see Fig. 1. The first aspect, *interactivity*, considers the feedback loops between human(s) and the information system: a system that is adaptive to the information demand and offers intuitive handling has a high degree of interactivity. *Integration* is about the degree of automatized co-operation between components of a system through pipelines, like API's, but also about the width of the information spectrum that is covered. The more components co-operate and the more diverse information is offered, the more integrated the digital twin is. *Real Physics* covers the numerical simulation of physical processes, enabling forecasting the near future and hypothetical scenarios. *Real Data* is the foundation for digital twins. Continuous, high-quality real-world data streams are crucial for calibration, validation and predictive modelling ¹⁶. The *Social* aspect is about allowing involvement of multiple actors. Digital twins enable more inclusive decision making, allowing diverse stakeholders to explore scenarios together. The last aspect, *Photorealism*, is about the presentation of the information. The more realistic and intuitive the visualisation, the easier it is for stakeholders to understand information, align perspectives, and empathise with different scenarios.

While idealised digital twins consists of six aspects, in practice, large-scale digital twins of environmental systems, typically only consist of some (rather than all) aspects. EDITO promises to offer all six aspects when operational. EDITO's foundation are *real data* (e.g. in situ observations in EMODnet, satellite observations in Copernicus Marine) and *real physics* (scientifically validated tools, see section Methods). EDITO's main advancements over the last years were on the aspects of integration (see section EDITO platform integration) and interactivity (e.g. EDITO Datalab) and recent EDITO explorative work includes photorealism (e.g. three dimensional and other innovative visualizations). For the social aspect, we see examples of involvement of multiple actors, for instance via the Digital Ocean Forum, even if it is at an early stage.

This paper shows how application integration into EDITO turns models and observations into policy-ready services for a large spectrum of topics in the marine domain. The presented EDITO applications offer practical support for policy issues like Marine Protected Area planning, biodiversity conservation, decarbonised marine transport, and pollution (risk) management. Other policy goals could also be served by such applications. Beyond describing the application outputs and their added value, the paper also offers insights into application design choices, and derives shared learning points from cross-application analysis.

The paper is structured in line with the Theory of Change framework ¹⁷. As shown in Fig. 2, we aim to showcase that building on scientifically validated tools and data (inputs) and investing in reusable, standardised, and modular modelling workflows in parallel to co-design and application development (activities) enable scalable applications and informed decision-making (outcomes), ultimately better contributing to policy goals (impact). The Results section of this paper corresponds to outputs, the Discussion focuses on the resulting outcomes and reflects on potential impacts, and finally, the Methods section describes the inputs and activities.

Results

- Application outputs

The results described in this paper were accomplished within the framework of the EDITO-Model Lab project (<https://edito-modellab.eu/>). EDITO-Model Lab provided the “core model suite” for EDITO, consisting of validated scientific processes, such as numerical- and AI-based models (see Section on Scientifically validated tools and data). The added value of the core model suite was demonstrated in several applications (summarized in Table 1) supporting the EU’s Nature Restoration Law, EU Biodiversity Strategy, EU and International Maritime Organization (IMO) maritime decarbonisation goals, Marine Strategy Framework Directive (MSFD) Descriptor 10 reporting, as well as offshore safety and emergency response.

Table 1
Overview of the EDITO applications presented in this paper, targeting different domains and policy goals. Applications tutorials can be launched by clicking on the application titles.

Application	Domain	Policy	Information offered	Targeted audience	Relocatable
Habitat Suitability Mapping for user defined species	Nature, Biodiversity	EU’s Nature Restoration Law (30x30 marine conservation target)	Habitat Suitability maps for seagrass (<i>zostera marina</i>), shellfish (pacific oyster), and any other user defined species and custom assessment periods	Scientists and practitioners at national and international agencies	Globally
Biodiversity indicators	Nature, Biodiversity	EU Biodiversity Strategy	Biodiversity potential based on near-bottom oxygen, chlorophyll and nutrient concentrations for custom assessment periods	Regional environmental agencies	Regionally
Pacific Green Corridor	Maritime transport	EU & IMO maritime decarbonization	Plots and metrics of least-distance, least-time and least-CO2 emission routes, based on 10-day forecasts	Operational planners and shipping companies	Regionally
Fate & pathways of microplastics	Pollution	EU Zero Pollution Action Plan MSFD Descriptor 10	Multi-year diagnostics: Fate and pathways of land microplastics in the Baltic Sea, spatiotemporal distribution, residence pattern, microplastics budget for user specified area	Environmental protection agencies, research community	Regionally
WITOIL Cloud	Pollution	Emergency response support	Deterministic oil spill hazard indices for up to 4 days of length: cumulative oil spill trajectories, oil fate on the surface, oil mass on the coast. Simulation Mass Balance.	Emergency response / coast guard	Globally
Oil Hazard Mapping	Pollution	EU Directive on Offshore Safety	Oil spill hazard maps and indices derived from probabilistic simulations (over five years)	Planning agencies	Regionally

The applications covered various European Regional Seas and beyond (see Fig. 3). The criteria for selecting geographical domains for the applications was the urgency of the environmental and societal challenges in those domains while ensuring the coverage of various European Sea Basins or geographical domains of operation of European companies.

The **habitat suitability mapping application** (demonstrated and validated in the Dutch Wadden Sea for the year 2017) maps habitat suitability of selected species based on simulated environmental fields. It aims to support policy makers in effectively (re-)assigning the targeted Marine Protected Areas and (re-)defining active legislation that facilitates the EU Biodiversity Strategy and other international goals such as the those in the EU's Nature Restoration Law, that states that 30% of the ocean should be conserved and 30% of degraded ecosystems need to be restored by 2030.

The main added value of the application is the simplification of the entire process of creating local habitat suitability maps at the coastal scale. Currently such tools and workflows are complex, costly, and hard to access even for intermediate users. Via EDITO, free access was provided to advanced modular (pick and choose) simulation tools leveraging its computational infrastructure. With this application intermediate users can produce maps on-demand anywhere on the entire global coast, for any species and ecosystems, as long as the user has basic understanding of the local physical system and ecological response to physical conditions. Relocation is facilitated by global data products that are offered by among others CMEMS, ECMWF, and GEBCO. The assessment periods needed to base habitat suitability mapping on can vary from seasonal to climatological multi year periods. This poses criteria for the on-demand simulations of the underlying physics, which in turn decides if the on-demand simulation can be run on the EDITO cloud or on HPC. The intermediate users can support end-users by reusing (components of) this workflow to effectively plan MPA's, thereby optimizing biodiversity protection and restoration with habitat suitability maps.

Similarly, the **biodiversity indicators** application (demonstrated and validated in the German Bight for the year 2020) is a swift and robust tool to assess the habitability or biodiversity potential tailored for a subregion of the underlying numerical model domain. Marine biodiversity is of particular importance in the United Nations Sustainable Development Goals (SDGs), EU Biodiversity Strategy and the Green Deal, the main European initiative to mitigate climate change, as many Green Deal activities affect marine ecosystems, such as the construction of offshore wind farms.

The application utilises model data derived from a verified numerical model applied to custom assessment periods, empowering users to establish their own evaluation criteria through the configuration of customised thresholds for ecologically significant variables. Users have the capability to customise their assessment according to their region, interests and experience, and to repeat it as frequently as required. The application's versatility lies in the fact that users can enter their own regionally applicable or future projected thresholds for biodiversity indicators, such as nutrient concentrations. The application integrates these user inputs to produce an assessment of biodiversity potential on a scale of 0 to 100, with values above 50 indicating positive potential. In this way, the application allows users to use not only currently regionally valid thresholds as the basis for the assessment, but also future expected thresholds and limits, accounting for climate change. In conjunction with the seasonally dominated dynamics of regional ocean biogeochemistry, the application thus demonstrates generic power without relying on extensive numerical model simulations in the background.

Another application in the domain of maritime transport is the **Pacific green corridor** service aiming to maximize operational efficiency at sea which is vital for both conventional and clean-fuelled vessels. Rough seas not only pose navigational risks, but also lead to unintentional speed loss, route diversions, and increased emissions. Ocean currents, while useful for enhancing speed when fair, can significantly reduce speed over ground if encountered at unfavourable angles. To address this and support the EU & IMO maritime decarbonization strategy, the application integrates high-resolution environmental forecast data, an open-source ship weather routing model and a cloud-based digital twin infrastructure. The application enables maritime stakeholders to operationally reduce CO₂ emissions and fuel consumption leveraging wave and ocean current forecasts, thereby advancing maritime decarbonisation goals in a practical and scalable way.

This is demonstrated across the North Pacific, which hosts the Shanghai–Los Angeles Green Shipping Corridor, a major trans-Pacific green shipping corridor initiative. However, the solution can easily be relocated to other world oceans, leveraging global Copernicus reanalysis (historical) and forecast data products available on the EDITO Data Lake.

The **Baltic Sea microplastic fate and pathway application** aims to bridge the gap between hydrodynamic modeling and environmental governance by directly operationalizing indicators required for the Zero Pollution Action Plan and MSFD Descriptor 10 on marine litter. One major challenge for assessing microplastic risks in marine environment is lack of data. Existing marine microplastic observations are very sparse and measured with different technology standards¹⁸. The application offers scientifically validated tools and data products (validated for the period 2014–2019) for users to assess the spatial and seasonal dynamics of multi-types of microplastics in their region of interest. Users are enabled to track microplastic sources, to identify pathways and accumulation zones and support the design of efficient pollution combatting and mitigation strategies. By integrating high-resolution ocean model outputs with cloud-based digital twin infrastructure, the service transforms complex microplastic distribution data into actionable insights for pollution source attribution and mitigation strategy prioritization. This modular approach can be relocated to other marine regions, pollutants, and particle transport applications.

For the topic of oil spills, two applications were developed. The **WITOIL cloud** application (demonstrated and validated in the Mediterranean Sea) provides accurate forecasting and simulation of oil spills, which is critical to mitigating substantial environmental, economic, and social risks by enabling timely responses to contain and reduce potential damage. Moreover, it plays a crucial role in shaping proactive response strategies, supporting resource allocation, and informing cleanup operations. The application offers an open and accessible oil spill simulation system that requires almost no prior knowledge to launch hypothetical or real oil spill events all over the world. It reaches different stakeholders, mostly those who have no experience in programming languages, to investigate oil spill impact in their area of interest. Currently, the application allows users to launch simple point source simulations for up to 4 days length, aiming to provide a first and quick assessment for deterministic oil spill simulations.

The **Oil Hazard Mapping** application aims to identify the most probable oil accumulation hotspots both along the coast and in the open ocean following a user-defined oil spill release location based on postprocessed results originating from 200 release points in the Mediterranean Sea. It uses a probabilistic approach with multi-model ensemble simulations, which accounts for uncertainties such as the exact timing, location, type of oil and variability in ocean currents. It simulates oil transport and transformation from multiple coastal release points over five years (current simulation period is 2018–2022) and calculates oil trajectories and beaching events. The resulting ensemble of oil concentrations is used to create different hazard maps and indices displayed in an interactive viewer. It is possible to extend the release points and the simulation period by making them available in the EDITO storage dedicated to the application. The same way it is possible to use other simulation periods. The application uses historical reanalysis data products of ocean currents and wind speeds.

- Cross-application analysis

While each application itself provides valuable scientific or technical insights, this paper aims to focus on overarching learnings by analysing design-choices in application architecture, user interfaces, relocatability, and modularity. In line with the philosophy of EDITO, all applications are FAIR. All applications are centralised as they are published on the EDITO platform (*Findable, Accessible*); EDITO integration required all tools used for the application to be standardised with containers, APIs, and integration templates (*Interoperable*); and finally all applications were documented with interactive tutorials and their input configurations as well as their output data are openly shared (*Reusable*).

All applications use EDITO Processes and Services as building blocks (see Table 2) but they have varying degrees of modularity. On one extreme, the Habitat Suitability Mapping application is highly compartmentalized (component-based), meaning that each step of the application can be executed separately, or skipped and replaced by similar EDITO Processes or data generated by external tools. This creates a versatile application where users can freely adapt the workflow. However, this freedom comes with the requirement that the user is enabled to operate the individual technical components and perform the necessary adaptations. Other applications, such as the Pacific Green Corridor and WITOIL Cloud, chose a different application architecture. In those applications there is an integrated (all-in-one) service that handles the workflow execution. Here deviations from the pre-defined application workflow are not possible. This results in a robust and efficient

application with low barrier to entry for users. Such architectures do not require manual execution of workflow components, instead it is handled by the application itself using the Process and Service APIs. For instance, once the inputs are selected by the user, the Pacific Green Corridor Service launches and retrieves the results of the VISIR-2 ship routing model programmatically, via the Service API.

Additional to the Process- and Service APIs, EDITO offers APIs to interact with the Data Storage and the Data Catalog. All applications store their outputs on the EDITO Data Storage and publish them on the Data Catalog and therefore make use of those APIs.

Tightly linked to the modularity philosophy of the applications, they work with different User Interface (UI) choices. A group of applications (Pacific Green Corridor, Microplastics fate & pathways, WITOIL Cloud, Oil Hazard Mapping) make use of interactive and user-friendly web interfaces. This allows users to work in a self-contained environment where all functionalities are intuitive and accessible in one place. This choice lowers the barrier for users and allows exploration without programming knowledge. Another approach was taken by the biodiversity indicators application that makes use of the EDITO Datalab UI. In the EDITO Datalab each process or service has configuration settings that can be adjusted by the users graphically. This application made use of the configuration settings to allow the specification of biodiversity thresholds and bounding box for the assessment. Yet another approach, taken by the Habitat Suitability Mapping application, was to make use of “low level interfaces” such as Jupyter Notebooks. Jupyter Notebooks allow structured and guided exploration of functionalities and execution of the workflow while keeping the flexibility of adjustments by the users themselves, but arguably only for those with programming knowledge. These UI differences (see Fig. 4) originate from different priorities in the design of the applications, resulting from different targeted interactions and even differences in targeted audiences.

Another important aspect of the applications is on-demand functionality to extend underlying simulations and assessment periods. Some applications, such as Habitat Suitability Mapping, Pacific Green Corridor or WITOIL Cloud are designed for user selection of model domain and time period. The latter two applications enable this directly in their UI, without leaving the main service. The other applications (Biodiversity indicators, Microplastics fate & pathways, Oil Hazard Mapping) are only designed to work for a given assessment period defined by their underlying datasets. It should be mentioned that EDITO Services and Processes in the Datalab have been developed for these other applications to enable users to perform extended simulations and update the datasets. This, however, remains a theoretical possibility since their target audience might not possess the necessary advanced skills to perform those simulations.

Table 2
Cross-application analysis

Application	EDITO Processes/Services used in the application	User interface	On-demand execution
Habitat Suitability Mapping	-Delft3D-FM Modelbuilder Service, -Delft3D-FM cloud/HPC running Process, -D-Eco Impact cloud running Process, -Post-processing Notebook Service.	Jupyter Notebooks, EDITO Datalab	Yes (via Datalab)
Biodiversity indicators	Biodiv-Explorer-Job Process	EDITO Datalab (process Configuration)	Partially, not in the UI (via Datalab)
Pacific Green Corridor	Pacific-green-corridor Service	Web UI (Streamlit)	Yes, in the UI
Microplastics fate & pathways	Baltic-sea-microplastics-viewer Service	Web UI (Streamlit)	Partially, not in the UI (via Datalab)
WITOIL Cloud	Witoil-cloud Service	Web UI (Streamlit)	Yes, in the UI
Oil Hazard Mapping	Hazard-map-viewer Service	Web UI (Streamlit)	Partially, but not in the UI (via Datalab)

The above described choices in application architectures, modularity, user-interfaces and on-demand capabilities can be categorized into three application archetypes (Fig. 5): (1) applications to process and explore complex pre-calculated simulations, (2) plug-and-play workflows, and (3) integrated (all-in-one) applications.

Examples of archetype (1) are the Biodiversity indicators, Microplastics fate & pathways, and Oil Hazard Mapping applications. In these cases the user interacts with the service via a dedicated user interface (be it complex web UI or simple Datalab process configuration) to process and explore pre-computed simulations, including the computation of metrics. Application results are saved to the private EDITO Data Storage. As mentioned earlier, pre-computed simulations can be extended via EDITO Processes but outside of the applications.

The Habitat Suitability Modelling application provides an example of a plug-and-play workflow (archetype 2). Here the users do not work with dedicated web-interfaces, instead via the Datalab, they can launch a variety of workflow components (EDITO Processes and Services) to execute a workflow. Some of the workflow components have low level interfaces like Jupyter Notebook, while others can simply be launched and monitored via the Datalab. Results of each workflow steps are written to the private EDITO Data Storage.

Finally, archetype (3), showcased by the Pacific Green Corridor and WITOIL-Cloud applications, enables users to launch a single integrated application with web-UI that allows the graphical execution of the workflow, including input selection, simulation (via Process/Service API) and visualization of results.

The only feature that is outside of all three application architectures is the publishing of results in the Data Catalog. By default, each application saves datasets on a private EDITO Data storage and an additional step is required to publish them on the EDITO STAC Catalog.

Discussion

Through examples of EDITO applications in three policy domains, this paper provides insights into how the marine community of practice can make use of the EDITO platform to transform the way they develop-, host- and use digital applications. We argued that the integration of applications into EDITO consisting of reusable data tools and modelling

workflows brings positive outcomes for intermediate users by simplified scaling and replication, and for end-users by enabling informed decision making and policy action.

The (in)direct uptake of existing reusable workflow components on EDITO by intermediate users clearly speeds up their application development efforts. While EDITO was only launched publicly in 2024, by June 2026 EDITO already offered 64 published services; 18 published processes and 14 published applications. Many more services, processes and applications have been developed and deployed on the back-end of EDITO but not yet published. This is an intentional functionality of EDITO, where users can create third-party applications but do not necessarily have to contribute and publish them for the community. During the EDITO-Model Lab project hackathon all teams were able to develop applications that executed processing steps on EDITO, (re)using components from the EDITO applications presented in this paper. In the evaluation of the hackathon, the participants clearly acknowledged that the existing applications served as building blocks on which a wide range of other applications could be built.

Following various interaction with researchers and intermediate users (see Methods, subsection Co-Design), the applications have been reused by institutes that advice local governments. These institutes were not involved in the development of the workflow, nor its components, but they are building with and upon the applications.

Positive feedback from policy makers indicated the perceived potential of EDITO applications to support more informed policy action. For example, at the Digital Ocean Forum and the Mission Ocean and Waters Forum, policy officers of the European Maritime Safety Agency (EMSA) and the European Commission's Directorate General for Research and Innovation (DG RTD) expressed interest in the ship routing application and its potential contribution to reducing carbon emissions. The underlying software, VISIR-2, was also recognised as a Mission solution¹⁹ under the EU Mission "Restore our Ocean and Waters". Across these and other policy-oriented events, including the One Ocean Science Congress and the 2025 United Nations Ocean Conference in Nice, stakeholder feedback highlighted the perceived scientific and technical credibility of the EDITO applications and their potential to translate scientific research into operational tools for stakeholder engagement and policy action.

Then Commissioner for Innovation and Research, Iliana Ivanova, presented EDITO's pre-operational platform at the Digital Ocean Forum 2024 and described it as a "game-changer in ocean management"²⁰, while it was deemed *"An amazing tool that helps us better understand the ocean, from pollution to navigation, from risks to our coasts to biodiversity"* by European Commission President Ursula von der Leyen during the United Nations Ocean Conference in Nice, France²¹. Underscoring the use of EDITO in the three policy domains (biodiversity, navigation, pollution) highlighted in this paper is an especially relevant acknowledgement. Political support from European level decision making also translates into long term sustainability of EDITO and its applications, especially that the European Ocean Pact formally endorses the delivery of a fully operational European Digital Twin Ocean by 2030 and highlights its role in driving science-based ocean governance. EDITO's role was further strengthened by the recently announced OceanEye initiative²².

Apart from European level endorsements, regional intergovernmental initiatives are also increasingly recognizing the role of EDITO. For instance, the Greater North Sea Basin Initiative Ministerial Declaration²³ by The Ministers of Belgium, Denmark, France, Germany, Ireland, the Netherlands, Norway, Sweden and the UK, in the presence of the competent European Commissioners specifically proposed to host and further develop their information service tool for the Greater North Sea Basin within the EDITO environment.

Limitations

We have demonstrated that integrating applications into the EDITO platform offers numerous benefits. Still, we see some limitations to the materialisation of the full potential. The EDITO platform is built upon external, open-source components. The evolution of and access to these components cannot be fully controlled, resulting in the evolutionary, non-static nature

of the platform and therefore in potential maintenance for the EDITO services, processes and applications to stay operational.

Moreover, although EDITO already hosts a wide range of models and pre- and post-processing tools (e.g. for visualization and validation), creating opportunities for their reuse in new workflows, compatibility and interoperability between these tools are not always guaranteed. Adhering to common standards and conventions and homogenizing input and output formats are therefore essential to move beyond a fragmented landscape of single-purpose, siloed tools in EDITO.

In terms of barrier to entry, participants in the EDITO-Model Lab Hackathon encountered challenges in troubleshooting services and processes and were often unsure how EDITO could be integrated into their operational workflows due to limited familiarity with the platform. These experiences highlight the distinction between scientific application development and the cloud engineering expertise required to operationalize and integrate applications within EDITO. Although the onboarding process is being streamlined through improved documentation, training materials, and AI-assisted support (e.g. chatbot), a certain level of technical complexity will remain for intermediate users seeking to contribute data, models, or applications to the platform. To help address these challenges, the EDITO Model Lab Hackathon Training Modules Wiki was developed, containing documentation and best-practice guidance for users.

A key current limitation for uptake of applications through EDITO is the availability of computational and storage resources. As the user base grows, demand for these resources is expected to increase accordingly. To manage this demand, users are currently allocated limited resources upon request, which are sufficient for testing and demonstration purposes but do not fully support the requirements of large-scale and computationally intensive applications. One potential solution is to strengthen integration with external public and private computing and storage infrastructures. Initial steps have already been taken in this direction: the Datalab can connect to external cloud storage (MinIO buckets) for alternative storage and to HPC clusters through the Autosubmit workflow manager ²⁴, providing near-seamless access to additional computing resources.

Future outcomes and impacts

It is expected that the presented applications will not remain static in their current form, instead they will be further developed, transformed by the application teams themselves and third parties alike to tailor them to future needs. The evolution of EDITO applications is partly an organic process, and partly managed, as EDITO team is putting many support systems into place, like the Project Forum that specifically aims on enhancing an active contributing community of users.

We also foresee that integrating into EDITO will not only remain a policy wish or technological push but will become a viable business model for existing applications. For instance, that was the case for the Horizon Europe CoCliCo project (<https://coclicoservices.eu/>) delivering Coastal Climate Core Services, developed independently but migrated to EDITO at the project end for continuation of availability of the CoCliCo data, -tools and -services. For most research applications the benefit over hosting elsewhere is simply cost-effectiveness. The tendency for integrating third party data, models and applications will be further accelerated by the new EDITO calls for additional applications. That is when the real power of such scalable, standardised and interoperable digital ecosystem will be utilized.

Future EDITO applications are expected to evolve towards more integrated and federated applications architectures than those presented in this paper, particularly as the diversity of EDITO contributors grows. In this architecture, application managers (or workflow orchestrators) act as an intermediary layer between the user interface and the underlying EDITO services, coordinating data exchange and execution across multiple building blocks. This represents an evolution of Archetype 3 presented in this paper, extending the concept of integrated applications towards complex multidisciplinary workflows that combine services from multiple contributors. Figure 6 illustrates this emerging archetype, in which existing and future EDITO services are coordinated through an application manager to deliver a seamless user experience.

Beyond more integrated application architectures, another future direction of EDITO applications will be the regional anchoring of EDITO by delivering regional digital twins. This not only recognizes the shared needs and priorities of regional (sea basin) communities but also the need for those scientific communities to jointly work on region wide solutions. This vision will be delivered in the coming years by projects under the EU Mission Ocean call for 'Regional (sea-basins) components of the EU Digital Twin Ocean'.

Methods

Scientifically validated tools and data

The backbone of the presented applications is the **EDITO core model suite**, a comprehensive suite of ocean numerical models and configurations designed to deliver high-resolution downscaling from the global ocean to coastal zones. The suite includes models for global ocean circulation (e.g. NEMO), for coastal oceans (e.g. Delft3D FM, SCHISM, HBM, SHYFEM-MPI, SFINCS, XBeach), but also "downstream models" for ecological impact assessment (e.g. D-Eco Impact), ship weather routing (e.g. VISIR-2) or oil spill (MEDSLIK). For several of these numerical models automation tools have been developed for rapid deployment across different geographic regions. Some of these tools have Graphical User Interfaces, such as SURF or HBM, while others are Jupyter Notebook based like the Dfm-modelbuilder. These tools incorporate automated downscaling procedures to refine large-scale model outputs for regional studies, accessing essential data inputs from sources, like the Copernicus Marine Service, ECMWF, EMODnet and additional data from third parties. The core model suite has been enhanced for the applications by improving process parametrization, improving ocean configurations, and ensuring optimized compatibility with High Performance Computing (HPC) hardware and graphics processing units.

- EDITO platform integration

All presented applications and their underlying components were deployed on the EDITO platform (see section on Code availability). They are freely accessible from a *single entry point* that is called the **EDITO Datalab** (<https://datalab.dive.edito.eu/>). In order to integrate Processes and Services into the Datalab, they needed to be containerized (e.g. Docker container or Apptainer) and must be accessible via public container registries (e.g. Docker Hub, GitHub Container Registry, Harbor, etc.). The Processes and Services are then "linked" to the platform via integration templates, called Helm Charts. These charts interlace containerized elements, input arguments, resource (compute and storage) requests, handle version control, but also provide the content (texts, links, logos) for the visual elements on the platform user interface.

Helm charts replace custom one-time-use integrations with reusable, well-documented containerised workflows. A major advantage is that services, processes and datasets integrated into EDITO can be programmatically accessed and used in other EDITO or external services and processes via EDITO APIs (Service API, Process API, Data Storage API, Data Catalog API). This creates an integrated and reusable ecosystem of digital twin blocks that rely on a scalable infrastructure in terms of data storage and compute (cloud CPU/GPU and HPC). The underlying datasets are stored in highly compressed, cloud-optimized Zarr format arrays, registered in the EDITO Data Catalog, which is a Spatiotemporal Asset Catalog (STAC), and accessible directly via object storage for programmatic analysis and integration with custom workflows.

For each application a dedicated interactive tutorial page was created on the Trainings and tutorials page (<https://dive.edito.eu/training>), facilitating easier use and re-use. The tutorial pages of all EDITO-Model Lab applications follow a standard structure. They first describe the background of the application (including societal impact and intended use), then provide step-by-step instructions on how to execute it. This is assisted by images or video snippets and direct URLs to the EDITO Processes and Services. At the end of the tutorials a more detailed scientific background is provided for expert users.

- Co-design

The initial application designs were based on the domain knowledge of implementing partners, that were gained in past national and international projects. In those projects a diversity of use-cases were addressed and a multitude of users were served, through which the knowledge base was built. The initial design also built on various National (e.g. LTER-LIFE) and Regional (e.g. HELCOM and OSPAR) expert networks, various European networks such as the EuroGOOS Coastal Working group, Copernicus Marine Service scientific and advisory groups, and even Global collaborations such as UN DITTO, the UN Ocean Decade Collaborative Center for Ocean Prediction and Coastal Resilience, and the UN Ocean Decade CoastPredict programme.

To verify and refine initial application designs, user validations were organised on multiple occasions along the development process. During local (e.g. ILIAD Summer School in Morocco, Delft Software Days) and national events (e.g. Dutch North Sea Days), scientific conferences (e.g. European- and American Geosciences Union's General Assemblies, Ecopath 40 years, Ocean Predict, One Ocean Science Congress (OOSC)), and more policy oriented events such as the Digital Ocean Forum (2023–2025), 2024 UN OCEAN Decade Conference, and the 2025 United Nations Ocean Conference (UNOC3), results of the applications were discussed with stakeholders and feedback was obtained. Especially the OOSC and UNOC3 enabled engagement with a broad group of end-users as it brought together global leaders, scientists, innovators, entrepreneurs, and members from politics and civil society. The European Digital Ocean Pavilion itself welcomed 27,800 on-site visitors where EDITO applications were provided for exploration and feedback. The OOSC served as a platform to emphasise the foundational role of science in shaping future ocean governance, and highlighted the need for integrated digital tools, like EDITO. Multiple of the presented EDITO applications were showcased and discussed during the OOSC.

Moreover, targeted user engagement was part of EDITO-Model Lab project meetings. In January 2024, representatives of the European Environmental Agency and local Environmental Agency of Apulia region as well as representatives of local government (Province of Lecce), Marine Protection Agencies (Torre Guacento and Porto Cesareo), port authority of Taranto and the Gallipoli and Otranto Coast Guards joined the project meeting and provided feedback on the applications at an early stage. In March 2025, local scientists (representing IEO de Baleares and CSIC-IMEDEA), representatives of a local government agency (SASEMAR - Spanish state agency responsible for maritime search and rescue, vessel traffic control, and environmental protection), joined the project meeting and provided feedback on the applications at a more mature stage.

Beyond co-design, the EDITO-Model Lab hackathon was held in October 2025, targeting intermediate users (numerical modellers, programmers, researchers and data scientists) that were challenged to use the outcomes described in this paper and create novel applications. This innovation sprint was the largest capacity-building action. Forty participants, in eleven teams, representing institutes based in 8 unique countries across Europe and in the United States of America, validated EDITO's potential to swiftly scale outcome, by re-use of existing components of existing applications. The participating teams were challenged to develop applications that executed processing steps on EDITO, using components that were already part of the platform and adding novel components to the platform.

- Application development

Application integration into the EDITO platform supported the “FAIRification” of workflow components, while co-design ensured that the user requirements and feedbacks are reflected in the application design. In this section, we introduce per application how they were developed by describing the used methods as well as the scientific setup and validation.

The approach used for the **Habitat Suitability Mapping application** is relocatable and on-demand, meaning that with local coastal and ecological knowledge, it can be used anywhere around the world. This is achieved by using an automated model builder for Delft3D FM simulations that creates all the configuration files and the right file structure for a Delft3D FM simulation to be initiated on the EDITO platform. The Delft3D FM model simulates (part of) the necessary spatial data for the habitat suitability analysis. Other spatial data can be used to combine or replace Delft3D FM output, the only current constraint is that the data should follow UGRID NetCDF standard (<https://ugrid-conventions.github.io/ugrid-conventions/>), as in that case D-Eco Impact can directly process the data. D-Eco Impact is a Python-based kernel to perform spatial

(environmental) impact assessment. It enables users to use ecological knowledge (the response of species to a physical parameter like salinity) and compute the likelihood or suitability for existence of that species on a specific grid cell. This is computed for multiple knowledge rules and for all the spatial cells, giving resulting habitat suitability maps that can help policy makers with their restoration and conservation planning and action. Although globally relocatable, Deltares has validated this application for the Dutch Wadden Sea. To couple physical parameters to suitability for habitat species, ecological knowledge rules were derived from a public ecological knowledge base (see Data availability), and from additional sources^{25–28}. In the application tutorial the suitability of the Wadden Sea for Eelgrass (*Zostera Noltii* and *Zostera Marina*) is computed but similar assessments were also done for Pacific Oysters and Mussels. Validation was done using multiple research surveys on the Dutch Wadden Sea. The source for validation data for bivalves (mussels and Pacific oysters) was obtained from Wageningen Marine Research²⁹ and for Eelgrass from the Dutch National Seagrass mapping database (see Data availability).

The approach of the **Biodiversity indicators application** is to use a SCHISM-FABM-ECOSMO modelling framework^{30,31} to simulate the physical-biogeochemical marine dynamics in the southern North Sea with a focus on the German Bight. SCHISM³² is the hydrodynamic core, FABM³³ is a physical-biogeochemical coupler, and ECOSMO³⁴ is an ecosystem model for nutrients and low-level trophic interactions. For the development of the application, the simulation was initialized, calibrated and validated for the year 2020. The forcing consists on the one hand of oceanic reanalysis data from the AMM15 and NEMO models (available via CMEMS), atmospheric reanalysis data from the COSMO-EU model of the German Weather Service³⁵, and on the other hand of river data such as runoff and nutrients. The simulation with hourly output time step resolves ocean physics and biogeochemistry on tidal scales up to seasonal cycles and beyond. The model grid has a coarse resolution of 2–5 kilometre in the marginal and central areas of the southern North Sea and refines to 10 to several 100 meter in the German Bight and estuaries³⁶. The model outputs of the nutrients nitrate, ammonium and phosphate, as well as oxygen and phytoplankton, serve as the data basis for the application. The algorithm has been developed to combine efficient data processing with high scientific significance. The variables are sampled at the critical vertical position, i.e. nutrients and phytoplankton at the surface and oxygen near the bottom. The variables are also averaged over a query period, which by default is the whole year and can be limited to summer or winter months if required. On the EDITO Datalab, a Process Configuration tab allows the user to enter values for the geographical area of interest and ecological thresholds for oxygen, nutrients and chlorophyll. Upon launching the application, the platform accesses the underlying simulation data and applies the algorithm integrating the user-defined inputs.

The **Pacific Green Corridor** application addresses the need for optimized route planning by utilizing wave forecasts from both Copernicus Marine Service and uGlobWave simulations (realized within the EDITO-Model Lab project) and ocean currents from the Copernicus Marine Service, in conjunction with the open-source VISIR-2 ship routing model³⁷. The application is containerized via Docker, simplifying computational processes and delivering ready-to-use solutions directly to end-users. The ship weather routing, also known as voyage optimisation, is an operational technique designed to leverage marine weather information to suggest route diversions or intentional speed variations, to reduce fuel consumption and emissions. Both commercial and open-source systems exist to perform ship routing, with the primary aim of providing shipmasters with routes that offer specific benefits. These benefits often include reducing the overall cost of a voyage, minimizing sailing time, adhering to schedules, lowering greenhouse gas emissions, or ensuring navigational safety and passenger comfort. To achieve these objectives, a ship routing system typically suggests adjustments to the ship's course or speed at specific points along the route, known as waypoints. The system generates these recommendations using three critical components: (1) forecasts of weather and ocean conditions, (2) a vessel performance curve representing the ship's speed through water and fuel consumption under different marine and propulsion conditions, and (3) a shortest-path algorithm, which calculates the most efficient route based on the above inputs. VISIR-2 utilizes a graph-search algorithm that has been specifically evolved to handle dynamic edge weights, ensuring accurate and efficient route optimisation. The model's shortest path component has been validated through comparisons with analytical benchmarks and inter-comparison exercises. To improve route smoothness, for the Pacific Green Corridor application, graph edges are established

between each node and its neighbours, extending up to the sixth order³⁸. This allows a more refined and smoother route calculation by considering a broader network of neighbouring nodes.

In the **Baltic Sea microplastic fate and pathway mapping service**, to simulate the spatial and seasonal dynamics of marine microplastics, an advection-diffusion-sedimentation module was coupled with the relocatable HBMos-WAM coupled ocean circulation and wave model engine^{39,40}. The embedded microplastic module simulates 3D transport of microplastics by resolving wave and current induced transport, particle size and density dependent vertical motion, biofilm growth module to overcome the initial buoyancy of many plastic materials and removal processes due to sinking and sedimentation.

The model forces land-derived plastic pollution across three distinct particle categories: automotive tire wear particles (TWPs) and two separate classes of domestic household microplastics (high-density and low-density polymers). Riverine and coastal catchment discharge boundaries were parameterized using localized daily mass-loading source assessments¹⁸. These datasets quantify the daily mass flux of microplastics released across all primary river mouths and coastal catchments draining into the Baltic Sea basin. The transport model was tuned and validated against historical in-situ sampling arrays³⁹ to establish a stable, repeating seasonal equilibrium cycle under stationary source boundary conditions. The model has been tuned to reproduce a stable seasonal cycle for constant river sources. Comparisons with observations³⁹ showed that the model can capture the average spatial and seasonal pattern.

Multi-year diagnostic simulations were executed across two distinct temporal windows to establish the underlying digital twin data architecture: i) climatological baseline (2014–2019) to map long-term, high-resolution spatial and seasonal accumulation patterns; ii) budget and transport analysis (2018–2020) to derive high-frequency time series, transboundary transport vectors, and mass-balance budgets. The output array is parsed into four distinct computational functions, structured for downstream end-to-end integration. The microplastic climatological mapping generates spatial-temporal fields resolved as monthly mean climatologies derived from the 2014–2019 baseline data, and localized time series extraction on multi-depth microplastic concentration time series for any user-specified geographical coordinate. A dynamic viewer and download service has been developed to provide visualization tools and easy access to the comprehensive, high-resolution data sets.

The **WITOIL-cloud** application utilizes the MEDSLIK-II Lagrangian model, which simulates the transport and fate of oil spills in marine environments⁴¹. Beyond the technical implementation to port the model to a containerized environment for the first time, its scientific modules have been modernized to achieve faster and more maintainable pre- and post-processing needed for the oil spill simulations. The model integrates data from operational oceanographic services (Copernicus Marine Service) and weather reanalysis (ECMWF ERA5) and forecast (ECMWF open-data), enabling accurate simulations of oil spill trajectories, concentration fields and potential coastal impact, as well as the seasonal and spatial variability in spill dynamics. The modernization allowed the oil spill modelling system to be connected with SURF⁴² platform within EDITO itself, allowing to run downscaling simulations and later perform the oil spill simulations in these high resolution fields instead of using the available regional products⁴³. On top of that, it also allowed the model to be connected with Machine Learning applications⁴⁴ to assess how well parametrization through optimization procedures can increase the accuracy MEDSLIK-II simulations, illustrating how the modernization needed for EDITO enabled uptake in new scientific domains. Finally, in addition to these modelling capabilities, the application provides an online system with an intuitive user interface, based on Streamlit. This platform allows stakeholders, regardless of technical background, to launch simulations for nearly any maritime area in the present or past, making oil spill forecasting accessible and actionable.

The **Oil Hazard Mapping** application employs the MEDSLIK-II oil spill numerical model to simulate virtual spills every 5 days over a 5-year period (2018–2022) for each release location. The model setup represents a fixed, operational spill scenario across all simulations, where oil is released continuously at a rate of 0.17 tons/hour for a total duration of 120 hours. The average oil concentrations reaching the coastline and remaining at sea are then extracted from the resulting oil concentration distributions at each grid point. Additionally, to assess the probability of extreme oil concentration events

reaching the coast, a coastal hazard index was computed following an established methodology⁴⁵. Both concentration averages and hazard indexes are displayed in interactive maps.

Declarations

Competing Interests

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Author Contribution

The paper writing was initiated and coordinated by the main authors L.M. and F.D. All co-authors contributed to the content and to the revisions.

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Data Availability

Data availability Example outputs of the presented applications can be accessed via the EDITO STAC catalogue (endpoint is api.dive.edito.eu) and its interactive viewer (<https://viewer.dive.edito.eu/>). Links per application, describing metadata and including download links:

- Habitat suitability:

<https://viewer.dive.edito.eu/feature/https://api.dive.edito.eu/data/collections/FEDITO/items/Faa239eb1-70ee-5eb9-9e25-408cfffdbfa47>

- Biodiversity indicators:

<https://viewer.dive.edito.eu/feature/https://api.dive.edito.eu/data/collections/FEDITO/items/F09162fda-f68f-5700-89f6-d00e25779b6d>

- Pacific Green Corridor: https://browser.moregeo.it/external/https://minio.dive.edito.eu/oidc-msalinas/EDITO_FA2_Catalog/stac-catalog/catalog.json

- Fate and pathways of microplastics:

<https://viewer.dive.edito.eu/feature/https://api.dive.edito.eu/data/collections/Femodnet-microplastics/items/F1768c49e-8193-524d-b645-33bd14324137>

- WITOIL-cloud:

<https://zenodo.org/records/20811100>

- Oil Hazard Mapping:

https://viewer.dive.edito.eu/feature/https://api.dive.edito.eu/data/collections/Femodnet-additional_information_coastal_vulnerability_index/items/F0bec08b3-1aad-53b3-a7ea-42000226994e

For the habitat suitability mapping application, eelgrass distribution validation data was obtained from the Dutch National Seagrass mapping database: <https://maps.rijkswaterstaat.nl/dataregister/srv/dut/catalog.search#/metadata/095fc70b-11c3-4cb5-82da-454503fc7a13> and knowledge rules were derived from a public ecological knowledge base:

<https://publicwiki.deltares.nl/spaces/HBTHOME/pages/25722899/Ecological+knowledge+base>

Code availability All EDITO integration templates can be found on the Public EDITO Gitlab repository under <https://gitlab.mercator-ocean.fr/pub/edito-infra>

- Finalized processes are in Process Helm Charts, while the work in progress is in Process Playground.

- Similarly, finalized Services are in Service Helm Charts, with work in progress in Service Playground.

- EDITO Tutorials can be found under EDITO Tutorials Content: <https://gitlab.mercator-ocean.fr/pub/edito-infra/edito-tutorials-content>

Links per application:

- Habitat suitability- Delft3D-FM Modelbuilder Service: https://gitlab.mercator-ocean.fr/pub/edito-infra/service-helm-charts/-/tree/main/ocean-modelling/dfm-tools?ref_type=heads

- Delft3D-FM cloud running Process: https://gitlab.mercator-ocean.fr/pub/edito-infra/process-playground/-/tree/delft3dfm-custom-s3?ref_type=heads

- Delft3D-FM HPC running

Process: https://gitlab.mercator-ocean.fr/pub/edito-infra/process-playground/-/tree/delft3d-singularity-service?ref_type=heads- D-Eco Impact cloud running Process: https://gitlab.mercator-ocean.fr/pub/edito-infra/process-helm-charts/-/tree/main/metrics-and-indicators/decoimpact-process?ref_type=heads- Post-processing Notebook Service: https://gitlab.mercator-ocean.fr/pub/edito-infra/service-helm-charts/-/tree/main/data-visualization/dfm-postprocess?ref_type=heads• Biodiversity indicators- Biodiv-Explorer-Job Process: https://gitlab.mercator-ocean.fr/pub/edito-infra/process-playground/-/tree/biodiv_explorer_v2/biodiv-explorer-job?ref_type=heads• Pacific Green Corridor- Pacific-green-corridor Service: https://gitlab.mercator-ocean.fr/pub/edito-infra/service-helm-charts/-/tree/main/focus-applications/pacific-green-corridor?ref_type=heads• Fate and pathways of microplastics- Baltic-sea-microplastics-viewer Service: <https://datalab.dive.edito.eu/launcher/service-playground/baltic-sea-microplastics-viewer?name=baltic-sea-microplastics-viewer&version=1.0.21&s3=region-7e02ff37>• WITOIL-cloud- Witoil-cloud Service: https://gitlab.mercator-ocean.fr/pub/edito-infra/service-helm-charts/-/tree/main/focus-applications/witoil-cloud?ref_type=heads• Oil Hazard Mapping- Oil-hazard-mapping-viewer: https://gitlab.mercator-ocean.fr/pub/edito-infra/service-helm-charts/-/tree/main/focus-applications/oil-spill-hazard-mapping?ref_type=heads

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Figures



Figure 1

The six aspects of Digital Twins, defined by Fedor Baart, adopted from Dols et al. (2024)¹⁵.

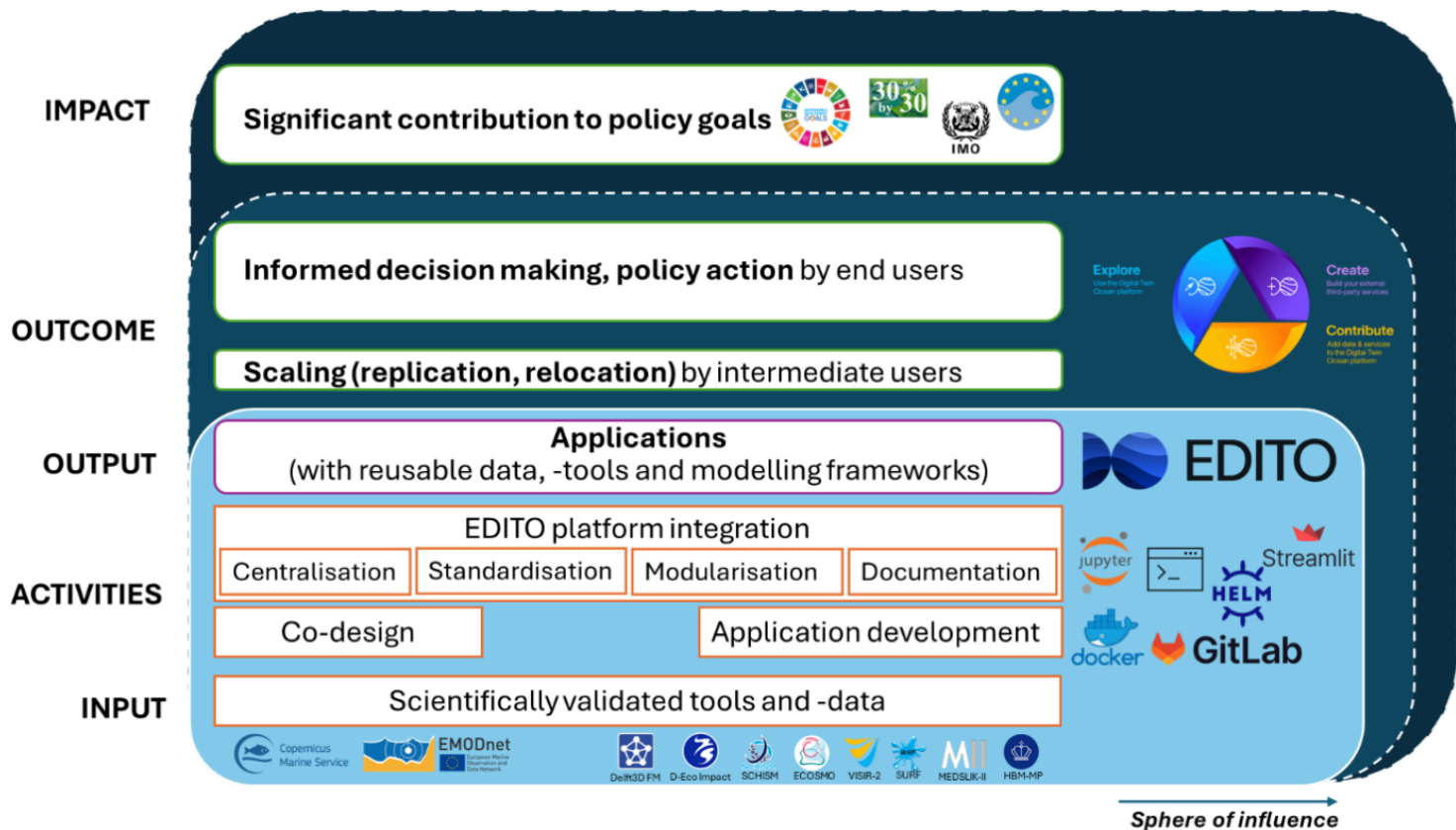


Figure 2

Conceptual roadmap of this paper following a Theory of Change approach. The figure organises key components into five categories (left), mapped across three spheres of influence. The innermost sphere (light blue) represents elements under direct control, which can be fully designed and implemented. The intermediate sphere (medium blue) captures outcomes that can be influenced (helped or hindered). The outer sphere (dark blue) reflects broader impact, which are beyond direct influence but are enabled by the system.

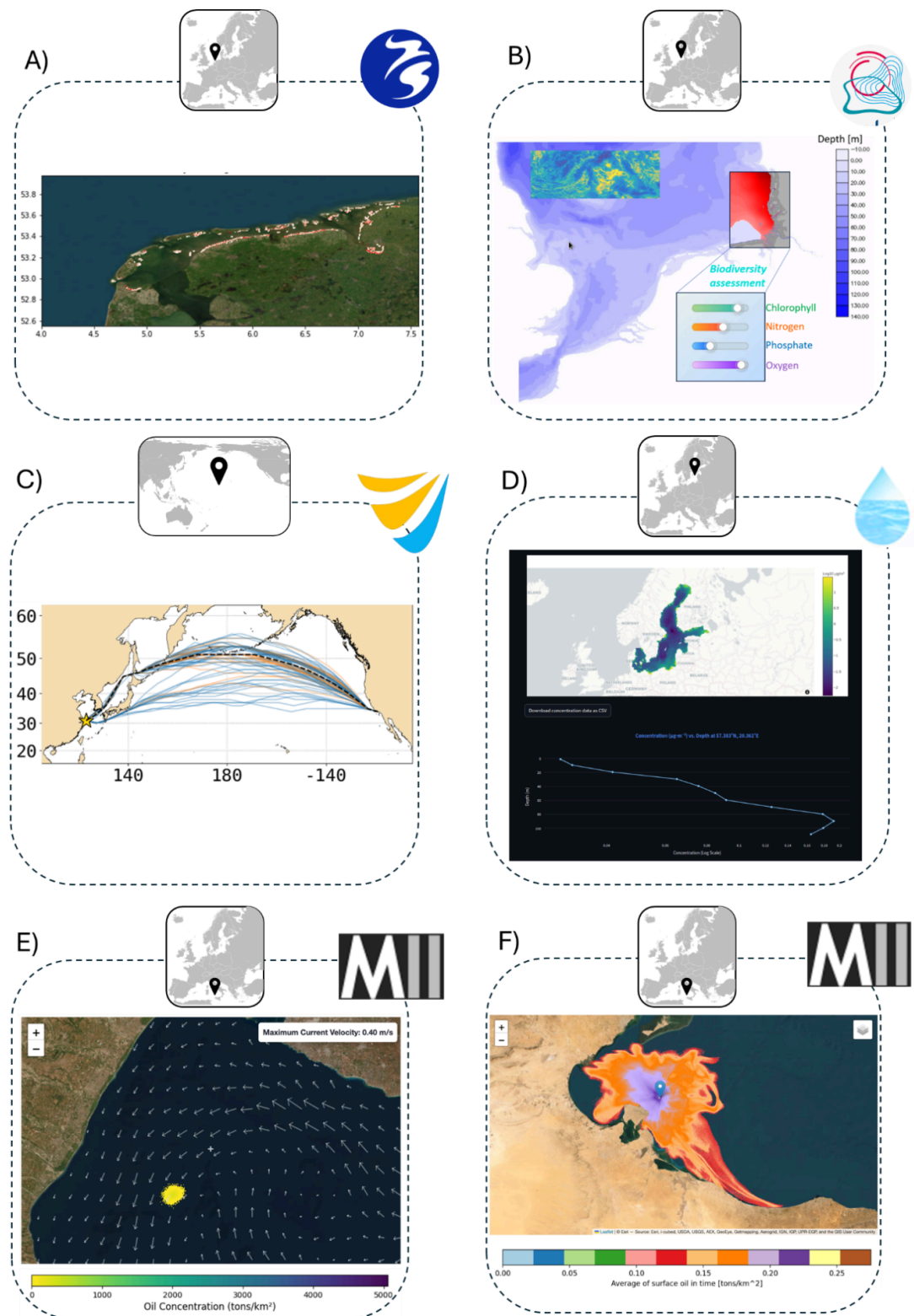


Figure 3

Example application outputs: Habitat Suitability Mapping by Deltares (A), Biodiversity indicators by HEREON (B), Pacific Green Corridor by CMCC (C), Fate and pathways of microplastics by DMI (D), WITOIL Cloud by CMCC (E), and Oil hazard mapping by UNIBO (F). Geographical locations of the validated cases are marked.

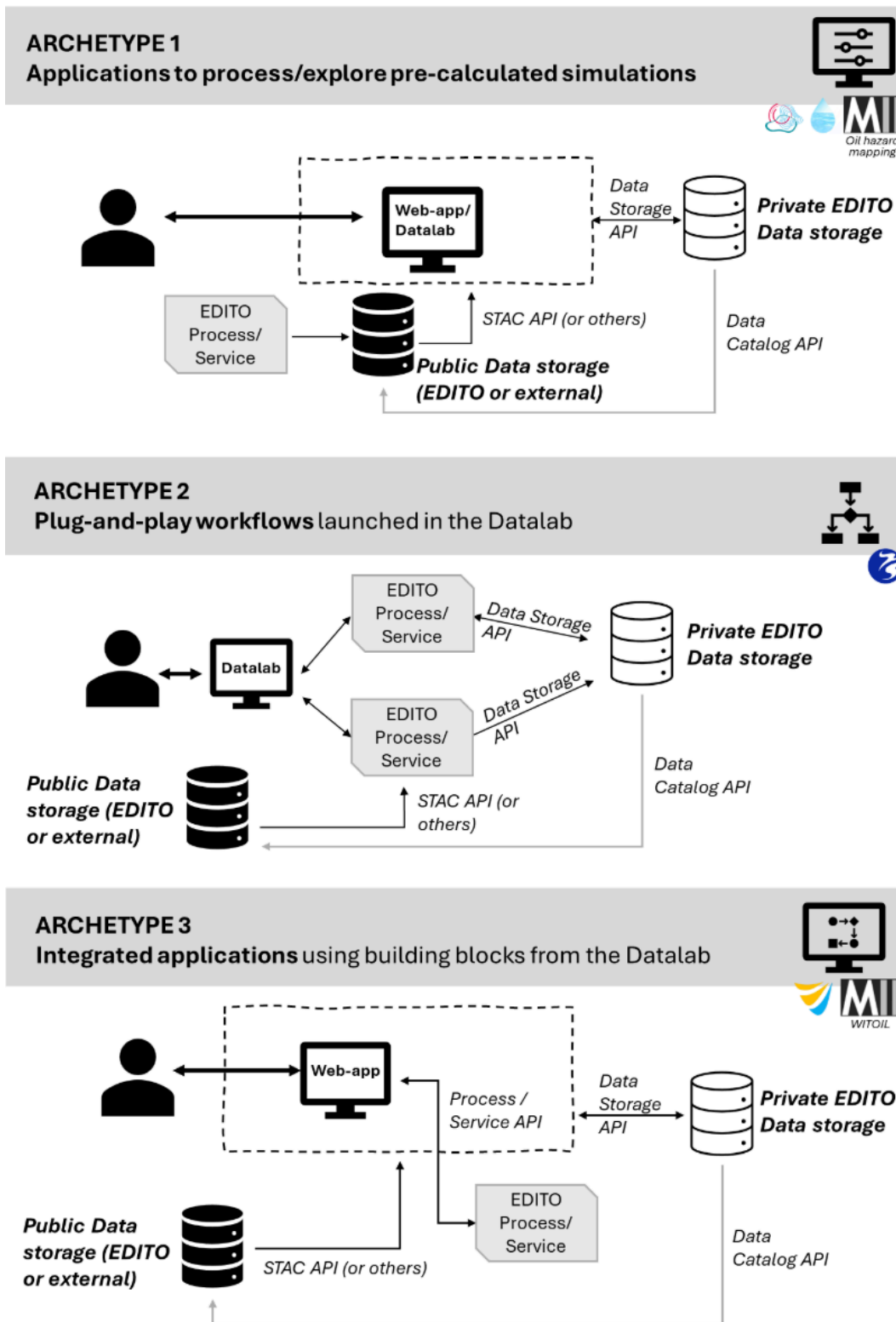


Figure 5

EDITO application workflow archetypes. The dashed box denotes the application layer, containing application-specific components, while EDITO Process/Service components are provided by the EDITO ecosystem. Applications representing each archetype are indicated by their logos.

Integrated and federated applications using application managers

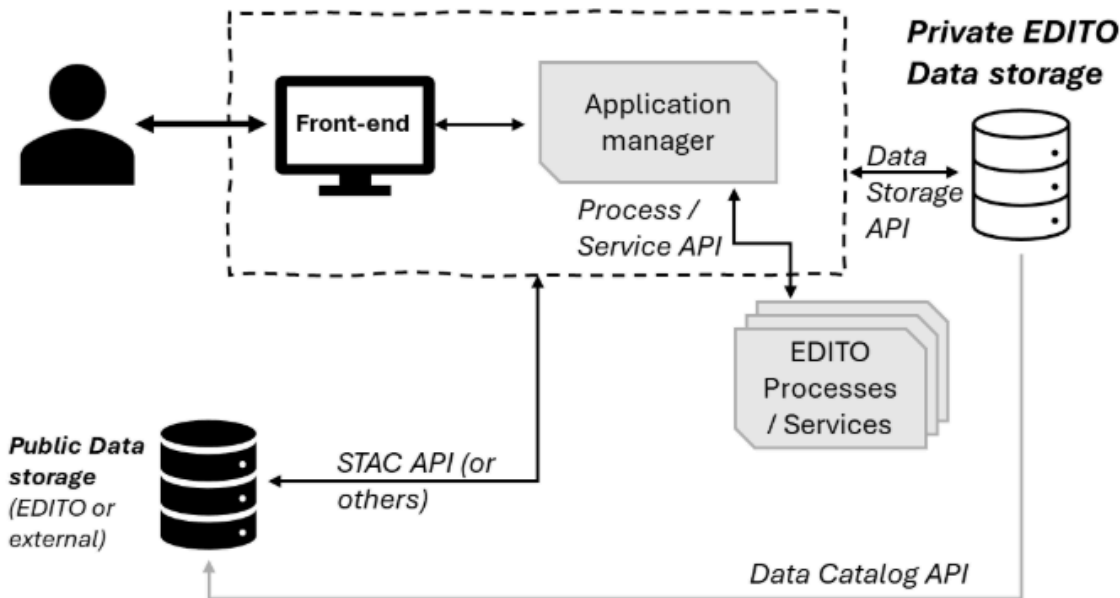


Figure 6

Integrated and federated application architecture using an application manager. The application manager (workflow orchestrator) coordinates interactions between the user interface and multiple EDITO processes and services, enabling the integration of building blocks contributed by different providers into a single user-facing application. This architecture extends the integrated application concept (Archetype 3) towards federated, multi-provider workflows. The dashed box denotes the application layer, containing application-specific components.