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Holistic Digital Twin of the Ocean

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ABSTRACT

The unsustainable exploitation of marine resources, the pollution caused by activities at sea and on land, and climate change threaten the health of oceans and seas, endangering natural heritage and socio-economic benefits. Addressing the transition to a sustainable marine economy while preserving biodiversity requires advanced, intelligent methods that can identify cause-effect relationships between pressures and responses within the marine ecosystem to estimate the ecosystem state and predict future conditions. Traditional Ecosystem Models (EMs) try to simulate the links between anthropogenic pressures, the environment, and the ecosystem status through heuristic approaches that require long development times and are seldom scalable and automatic. In this paper, we support the idea that Artificial Intelligence (AI) can help overcome these limitations by developing scalable and robust virtual representations, such as ”Digital Twins of the Ocean” (DTOs). A DTO models the ocean as a system of systems (morphological, geological, chemical, physical, biological, and socio-economic); its components process data flows to simulate the subsystems of a marine ecosystem and answer complex questions about its state, resilience, and responses to environmental and anthropogenic pressures, as well as the potential future biodiversity and ecosystem-service changes. One ultimate goal of a DTO is to support decisions by monitoring authorities with quality and details dependent on the available data.

Building DTOs is a major objective shared by European strategic agendas such as the Sustainable Blue Economy Partnership and the Mission Restore Our Oceans and Waters. Some initiatives already funded by the European Commission (e.g., ILIAD and EDITO) focus on data interoperability. Other partnerships (e.g., EMODnet and Copernicus) study models and generate data integral to DTOs. These initiatives follow general frameworks independent of a specific marine area. As a complementary approach, we propose a Multidisciplinary Design Optimization framework to model a DTO, scalable and adaptable to a marine area under analysis. It uses advanced AI models to combine data from diverse flows in real-time, adapting the models to the available data. Specifically, we present a *holistic* DTO modelling framework (*h*-DTO) - with prototype small-scale application examples - that combines AI models with physical/biological laws to simulate complex causal relations between the systems composing the analysed marine area. The AI models fill data gaps, automatically identify ecosystemic functional relations from the data (a task requiring significant effort and manual configuration in EMs), and simulate the complex interplay between species, natural resources, anthropogenic pressures, and ecosystem response. The *h*-DTO is also able to interoperate with other DTOs, adapted to different areas, to discover similarities in ecosystem responses and learn from mutual experience. Model interoperability in *h*-DTO requires Open Science compliance, i.e., model availability as web services following a standard descriptive framework. Additionally, data interoperability requires compliance with the ”Findable, Accessible, Interoperable, and Re-usable” (FAIR) directives. In this paper, we depict our modelling framework, compliant with these directives. Furthermore, we show prototype applications of h-DTO data gap filling and AI processes through case studies in the Mediterranean Sea to demonstrate how the bottom-up layers of the framework are built.