



Standards and Practices for the Iliad Digital Twins of the Ocean

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With increasing computing performance and data storage capabilities, Digital Twins of the Ocean (DTOs) support ocean research and management by improving simulations, monitoring, and predictions of ocean conditions and applications (from increasing sustainability of fisheries to oil spill response). DTOs are a new field, with various organizations and individuals developing them through their own, different approaches - from simulation models to data architectures to visualizations, but each DTO is created differently.

Standardization and development of best practices promote interoperability and comparability, enabling seamless connections between diverse data storage, models, simulation tools, and user interfaces from different sources and domains. This creates a trusted ecosystem with consistency, accuracy, and reliability, while allowing developers to improve their proprietary products. By defining common data formats, protocols metadata standards and vocabularies DTO actors collaborate more effectively, reduce redundancy, and minimize integration costs. It also promotes scalability, allowing digital twins to expand to more variables or more complex interactions without compromising quality. Models remain adaptable to new technologies and evolving scientific knowledge, enhancing their utility over time. Lastly, these approaches enhance transparency and reproducibility, building trust among stakeholders like policymakers, scientists, or the public.

Clear guidelines, standardization, and practice definitions in developing DTOs avoid fragmented efforts and drive global digital twin adoption, leading to more informed decision-making and better outcomes for environmental and societal resilience. Defined practices and standards for Digital Twins streamline processes across various fields and ensure interoperability of different DT environments. Converging and convening projects guide and validate technical and human interoperability layers of Digital Twins, including examples like:

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|----------------|----------------------|----------------------|
| - architecture | - sensor data ingest | - ethical |
| - data storage | - syntactics | - user experience or |
| - computing | - semantics | - design and |
| infrastructure | - legal | visualization |

These defined processes, development practices and standards, are expected to act as accelerators for DTO engineering and deployment, as they can shorten the implementation timeframes as well as speed up communication between engineers (within the project and other interoperable DTO environments). Practices and standards in this category support developers, engineers and other stakeholders through a shared taxonomy and well-defined process. Using such a common framework can reduce misunderstanding when collaborating and building interoperability into technical systems, as well as ensure that followed processes are comparable.

The Iliad project¹, a collection of localized digital twins of the ocean ('pilots'), employs various standards and best practices. Each pilot combines engineering processes and procedures from its topical sector (e.g., aquaculture, oil spill propagation, offshore wind farms, wave energy, citizen science) and digital systems engineering (e.g., data lakes, OGC APIs). The Iliad Consortium documents and collects and categorizes these practices in a 'compendium', with pathways to facilitate best practice documentation and standardization. This approach provides a 'birds-eye view' of existing and used standards and practices, supporting future DTO developers and potentially finding new approaches or collaborators. Newly developed practices and standards within Iliad are encouraged to be documented and shared with the broader digital twin and ocean research communities, for example on the Ocean Best Practices System OBPS², or in professional societies like IEEE Oceanic Engineering Society.

Mature practices, i.e. practices that have been well documented and widely used (see Ocean Practices Maturity Model³), may be adopted as formal standards within standards organizations that provide the needed ecosystem. The IEEE Working Group on a "Recommended Practice for the Development of Digital Twins of the Earth" (P3501⁴) aims to provide such a document for the broader ecosystem of environmental digital twins, including DTOs. It aims to provide sensible and useful engineering practices applicable to the development of interoperable digital twins, including the underlying reference architectures and components of DTEs; the interfaces between different digital subsystems; as well as related data and service models necessary to describe a digital twin, its functions and outputs as well as the interfaces (inputs and outputs) to other DTEs.

This paper discusses examples and the importance of DTO practices and standards, shares insights into the Iliad Compendium and provides an outlook on future possibilities for DTO development alignment between projects.

¹ Iliad Digital Twins of the Ocean <https://ocean-twin.eu/>

² OBPS: <https://www.oceanbestpractices.org/>

³ Mantovani C, Pearlman J, Rubio A, Przeslawski R, Bushnell M, Simpson P, Corgnati L, Alvarez E, Cosoli S and Roarty H (2024) An ocean practices maturity model: from good to best practices. *Frontiers in Marine Science* 11:1415374. doi: 10.3389/fmars.2024.1415374

⁴ IEEE P3501: <https://standards.ieee.org/ieee/3501/11771/>