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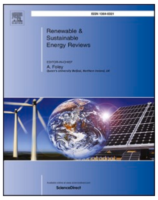

Marine energy digitalization digital twin's approaches

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ABSTRACT

Digital twins (DTs) promise innovation for the marine renewable energy sector using modern technological advances and the existing maritime knowledge frameworks. The DT is a digital equivalent of a real object that reflects and predicts its behaviours and states in a virtual space over its lifetime. DTs collect data from multiple sources in pilots and leverage newly introduced low-cost sensor systems. They synchronize, homogenize, and transmit the data to a central hub and integrate it with predictive and learning models to optimize plant performance and operations. This research presents critical aspects of DT implementation challenges in marine energy digitalization DT approaches that use and combine data systems. Firstly, the DT and the existing framework for marine knowledge provided by systems are presented, and the DT's main development steps are discussed. Secondly, the DT implementing main stages, measurement systems, data harmonization and pre-processing, modelling, comprehensive data analysis, and learning and optimization tools, are identified. Finally, the ILIAD (Integrated Digital Framework for Comprehensive Maritime Data and Information Services) project has been reviewed as a best EU funding practice to understand better how marine energy digitalization DT's approaches are being used, designed, developed, and launched.

1. Introduction

Population growth and human activity exert increasing pressure on Earth's vital resources such as water, food, and energy. This human pressure increases stress on ecosystems, health, and security [1]. Given the current situation, it is crucial to make precise and coordinated decisions and take actions for the humanity benefit [1].

The internet and information explosion technologies has created tremendous opportunities for those in library and information professions in higher education. In addition, geospatial information technologies have continued to evolve over the past few decades to support Earth's environmental science [2]. The desktop to Spatial Data Infrastructures (SDIs) and innovative technologies to realize the Earth digital vision from enhanced Geographic Information Systems (GIS), and Building Information Models (BIM) [3].

The ubiquitous connectivity promised by the Cloud Computing Paradigm (CCP), the Internet of Things (IoT), and innovations in Big Data (BD) could lead to disruptive changes in the design and development of data-intensive applications. Environmental applications often process extensive collections of data and datasets, for example, Earth Observation (EO) data from sensors with increasingly high spatial, temporal, and radiometric resolution combined with environmental models and simulations at large/standard/small scales [4]. Despite the continued data challenges in the ecological field [5], there is a need for comprehensive, adaptable, and expandable solutions that cater to a broader audience. This would promote multidisciplinary research in alignment with initiatives like Global System Science and Future Earth.

Overcoming the artificial boundaries between current sectors, linking existing systems, and overcoming technical and organisational barriers will be essential. Anticipating these developments [6], a paradigm shift towards a data-centric Environmental Observation Web (EOW) is proposed, where processing and modelling services are always modelled as observation data provided by humans and hardware sensors. The EOW should consider semantically enriched content, modularized environmental simulations, and citizen-supplied content. It should enable the use, production, and reuse of ecological observations in cross-cutting applications.

EO is important to provide information about planet Earth systems and the changes noted to preserve the human species. The EO summit of governments and international organizations committed to developing landscape designs for Earth's future was held in Washington, DC 2003.

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List of abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
BD	Big Data
BDS	Big Data Science
BOA	Bat Optimization Algorithm
BIM	Building Information Models
CCP	Cloud Computing Paradigm
DTs	Digital twins
DIA	Data Integrity Attack
DTO	DT of the Ocean
DL	Deep Learning
EO	Earth Observation
EOW	Environmental Observation Web
ECs	European Countries
ESA	European Space Agency
EGD	European Green Deal
EU	European Union
GIS	Geographic Information Systems
GEOSS	Global Earth Observation System of System
GEO	Global Earth Observation
IoT	Internet of Things
IaaS	Infrastructure as a service
IDS	Interactive Data Space
NASA	National Aeronautics and Space Administration
PaaS	Platform as a service
PLM	Product Life Management
PLCM	Product Life Cycle Management
RSM	Response Surface Methodology
SDIs	Spatial Data Infrastructures
SDGs	Sustainable Development Goals
SoS	System-of-Systems
SaaS	Software as a service
SCADA	Supervisory Control and Data Acquisition
UQ	Uncertainty Quantification
UN	United Nations

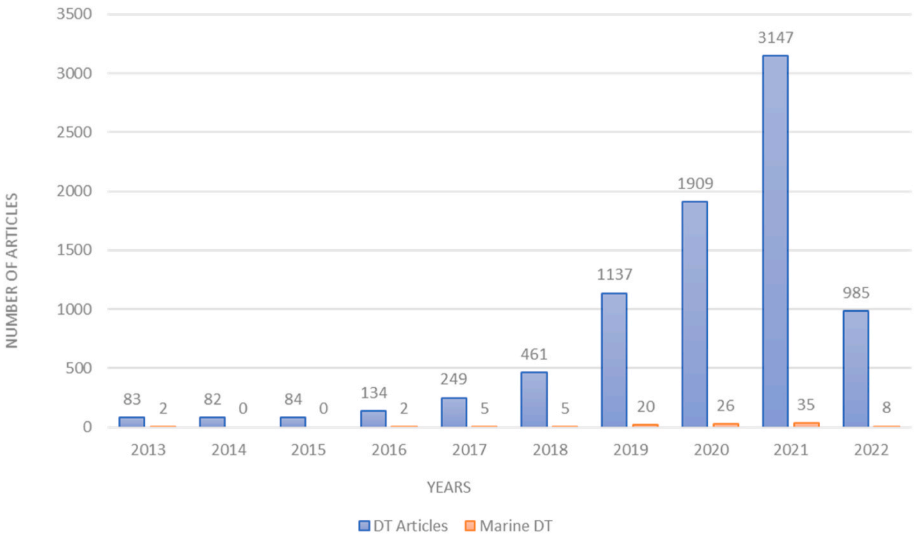


Fig. 1. The published articles trend with "DT" and "Marine DT" keywords indexed in the Scopus database from 2013 to 2022.

The United Nations (UN) Conference in Rio, Brazil (2012) created a high-level political forum for sustainable development for the international community.

In addition, the UN member states have decided to develop Sustainable Development Goals (SDGs). For example, the General Assembly of UN (2015) formally adopted the global, integrated and transformative 2030 Agenda for SDGs [7] with 17 SDGs and 169 related goals [8]. Shaping, implementing, and developing the SDG agenda requires information gathering, analysis, and sharing. The UN has called for the development of an internationally distributed knowledge platform to facilitate multilateral collaboration and partnerships to share information, practices, and policy recommendations among countries to achieve the SDGs with this aims [9]. In this regard, the European Space Agency (ESA) is planning and launching several groundbreaking activities on the Earth's Digital Twin (DT) to address the significant scientific and technical challenges posed by these developments, as described above.

These DT efforts include forest, hydrology, Antarctic, food systems, oceans, and climates. All DTs for oceans and seas will focus on the EO, sensors, and the Artificial Intelligence (AI) potential to learn directly from data acquired from different time periods (from the past to the present) and predict the Earth future behavior to predict events with parameters through real-time monitoring. The first step in the project DT can be a data-driven approach where numerical model results update observational data to visualize and analyze iterations of dynamical systems. In this context, numerical simulations, augmented by irregular sampling, will be used to assess long-term consequences at large to small scales.

The DT needs to be constantly updated and analyzed with EO data and datasets such as in-situ/on-site measurements, low cost sensors, and satellite remote sensing. This DT can help visualize and predict natural and human activities on our planet and will be able to monitor the Earth's health interconnected system by simulating human behavior and supporting environmental policies areas covered. The DT will make a significant contribution to economic and social well-being. According to the Fraunhofer Institute and the industry association Bitkom, the German market DT may be worth 267 billion euros in 2025 after the introduction of Industry 4.0 [10]. DT has also recently gained an increasing academic attention (Fig. 1). In this case, several studies have been developed for ships [11], ports [12], predictive modeling in wind turbines [13], wind energy sector [14], offshore structures [15], offshore platforms [16], renewable energy [17] and the marine industry [18].

The term "online platform" is used to describe a wide range of services available on the internet, such as search engines, application stores, communication services, social media, creative content stores, and payment systems. Online platforms are defined as a digital service that enables interaction between two or more distinct but interdependent groups of users who interact through the service over the internet [19]. Online platforms can be introduced as e-learning platforms that are created using internet technology. An online platform is a digital service that facilitates interactions between separate but interdependent users over the internet. Platforms can be viewed as places where supply and demand meet electronically [20]. The DTs develop common infrastructure and data space in the marine energy sector. In this context, the European Green Deal (EGD) scientific community and [19] the "European Strategy for Data" [21] have created common infrastructures and shared and interoperable data spaces across the European Union (EU) to address the challenges of environmental sustainability and digital transformation that they know is needed.

This study presents the concept of DT and the DT framework for marine knowledge using existing systems. The study discusses the different steps involved in developing DT, and identifies critical stages that include measurement systems, data harmonization and pre-processing, modelling, comprehensive data analysis, and learning and optimization tools. In addition, the study reviews the ILIAD project as the only innovative EU research project example of how DT approaches are used in marine energy digitalization in the several European seas. The project has been designed, developed, and launched as a best practice for comprehensive maritime data and information services. The foremost contributions are summed as follows:

- The DT and the existing framework for marine knowledge provided by systems are presented, and the main development steps of DT are discussed.
- The DT implementing main stages, measurement systems, data harmonization and preprocessing, modelling, comprehensive data analysis, and learning and optimization tools, are identified.
- The ILIAD (Integrated Digital Framework for Comprehensive Maritime Data and Information Services) project has been reviewed as a best practice to understand better how marine energy digitalization DT's approaches are being used, designed, developed, and launched.

This paper is organized as follows: 2. Modelling tools review*, 2.1. Software Desktop solutions, 2.2. DT Definition, 2.3. Society Digitally, 2.4. Earth DTs*. 3. Marine energy digitalization review*, 3.1. Artificial Intelligence-based DTs in renewable energy systems, 3.2. The DT Energy Framework, 3.3. Technological Knowledge Framework*. 4. A Thriving Marine DT: Principles and Patterns*, 4.1. Evolutionary Development of a Marine DT, 4.2. Marine DT Behaviour, 4.3.* Marine DTs systems geographical distribution heterogeneity. 5. Marine DT Mechanism. 6. Virtual Cloud Layers and Services*,* 7. DT platform launching*, 7.1. ILIAD as a Best Workout*. 8. Conclusions. All the acronyms utilised in this study can be seen in the list of abbreviations table.

2. Modelling tools review

This section provides an overview and surveys in the literature on the DT definition, the society's digital nature, and DTs. These are then categorized according to their respective focus areas and investigative approaches to highlight existing gaps in the literature.

2.1. Software desktop solutions

The computer's ability to understand the environment by receiving and processing images can be used for biological visual simulation. These devices and computer equipment can be used for scene reconstruction, video tracking, 3D position estimation, 3D scene modeling, and image restoration [22]. Significant progress has been made in various areas such as face recognition [23], smart locks [24], and buildings entrance and exit parts [25]. In this context, software desktop solutions can help researchers using Deep Learning (DL) to recognize devices and improve their understanding [26] and energy prediction [27]. For example, Zawadzki et al. [28], use a microprocessor controller for image analysis and remote control of optical beam direction. Shanmugam et al. [29] use integrated DL algorithms and computer vision to process video streams to study material transport in warehouses in their intelligent lighting control.

The GIS software layers data can be very useful to understand how the different infrastructures are arranged [30]. This is the case when the data and layers can be represented in BIM models as an essential element for the infrastructures and related design processes. GIS and BIM model software integration can be considered as the most fundamental need for the software functions integration, as they are not able to achieve all the different projects goals. GIS Layers and BIM model data integration can provide all coordinate systems, semantic standards, data formats, and other parameter information [31]. Many researchers have tried to improve the models data and functional performance by integrating GIS software and BIM model integration as best as possible [32]. The GIS software and BIM models integration can lead to time savings and real-time monitoring of the built environment projects [33].

Therefore, the models GIS and BIM, which develop and integrate technologies, have provided a more scientific and practical approach to planning and management [34]. Therefore, several previous studies have correctly explained how to extract information in BIM and 3D models to information models [35]. GIS and BIM software play an important and crucial role in the information correct management [36]. In addition, the CIM cadastral database creation is crucial for the information management development and maximum expansion such as, framework for automated model-based e-permitting system [37], and representation and visualization of 3D cadastre [38]. On the other hand, the GIS and BIM technologies integration in the cadastral management can help to strengthen and expand the modeling process BIM standardization and unify the information data formats used to facilitate it as much as possible in multi-analytical studies [39], and computer gaming environment [40].

Therefore, the BIM platforms and GIS technology integration is much better and practical [41]. Using BIM software cannot fully cover the project data management functions in the initial stage [42]. Therefore, the GIS technology should be used to simplify the BIM model and realize the construction visualization, management and other functions in the best way [43]. The GIS and BIM integration technology development, accompanied by other developments in IoT technology and structures, has increased the emergency response and construction speed to an acceptable level in worker safety [44], supply chain management [45], indoor spaces support adjacent analysis [46], and navigation applications [47]. Today, there is extensive research on the GIS software and the BIM models use integration in various sectors, such as projects related to water and hydropower protection [48], and design change model republication application [49], tunnels [50], bridges [51]. Based on the mentioned cases, it can be said that GIS software technologies and BIM model integration can be used as DT in projects as DT tools for digital information transformation.

2.2. DT definition

The first time a "twin" was mentioned was for the National Aeronautics and Space Administration (NASA) Apollo project (1960) in the space field [52]. This project NASA required the spacecraft to communicate with its twin on Earth as a "twin" in the same way as the other vehicle on a space mission [53]. It should be noted that digital aspects were not considered a "twin". The term "DT" was first coined by Michael Graves (2003) in his training course on Product Lifecycle Management

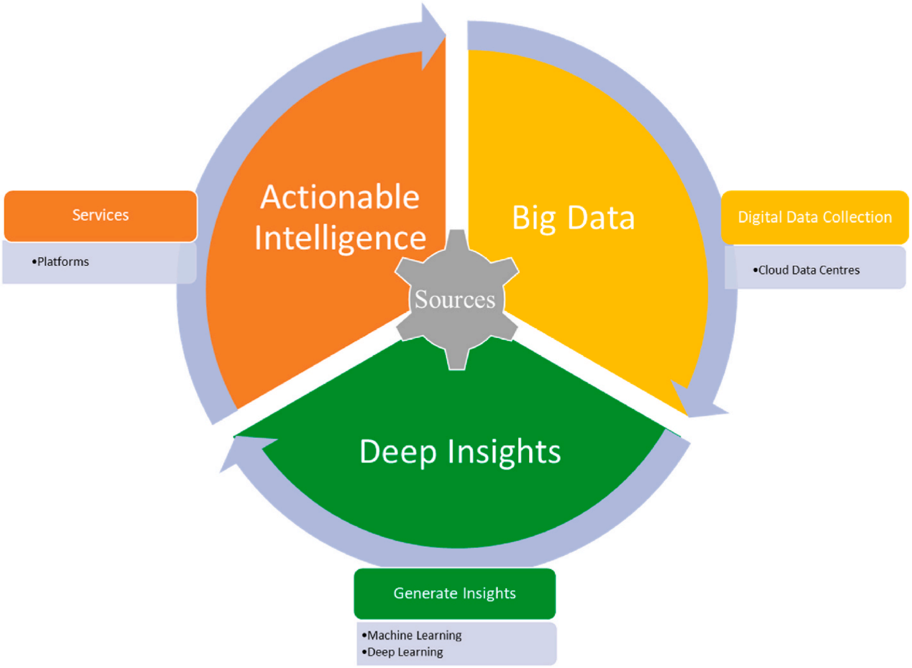


Fig. 2. Shows datafication paradigm to generate actionable intelligence streams.

(PLM) [54].

PLM management combines various business activities designed to use and modify the data obtained to cover all phases of PLM from design, production, maintenance and support to recycling and disposal [55]. In this context, Kritzinger et al. [56], describe DT as a digital information structure of a physical system as an entity related to the physical system. The various definitions and applications of DT describe this train of thought as a digital model related to a physical entity using smart devices and a digital model in a stable real-time communication network.

Different authors have presented different definitions to explain what DT technologies mean and what their goals are. Michael Graves defines DT as the reflective information model in product lifecycle management [57]. However, this definition does not provide a clear concept of DT. Several authors have developed the following DT definitions. Rosen et al. [58] introduced the definition DT, a combination of physical and virtual spaces that can reflect each other to evaluate physical lifecycle operations. Bushert and Rosen [52], explain that DT includes all valid physical and functional data of a system. Their description DT focuses on the data exchanges and algorithms that control physical behaviour and virtual models. This definition focuses only on the data from DT and ignores its components and purpose. Graves and Vickers [59] introduced DT as a set of virtual information structures in Product Life Cycle Management (PLCM) that convey the ability to represent a potential or actual physical product on a geometric plane. The DT goal is to realize the final product quality with digital design, which can reduce the gaps between design and implementation [59]. Compared to Griev's first definition [57], this definition provides more details about DT, but focuses more on PCLM.

Lui et al. [60], stated that DT is a living model that is a system that continuously adapts to changes based on collected data and information and can predict the environment physical future counterpart. A DT uses all tools, technologies, and internet systems to collect real-time data from the physical environment for simulation and virtual modelling. Madani et al. [61], stated that DT can be a virtual example of the performance, maintenance, and health of a physical environment that is constantly updated during the physical system life cycle. Loui et al. [60], stated that DT can be improved over time based on the updated information received from the physical environment and its performance monitored.

Undoubtedly, the DT platforms emergence will make new ways for functions and services in various fields more accurate and accessible. The DT Platform can be considered as one of the most promising digital discovery platforms [62]. The DT platforms field can be defined based on the interaction principle between the physical world and the virtual world, which enables data analysis and system flow monitoring [63]. This interaction between the physical environment and virtual modelling is greatly facilitated by communication platforms enhanced by real-time data and dataset updates. In this context, the IoT can be described as a highly reliable communication platform that uses sensors, cloud computing, and data analytics. The data and information transmitted flow between both parties can be referred to as the DT platforms essential part. This continuous flow of information between the physical and virtual environments enables the platform environment life cycle [64].

All these factors give DT voltmeters the ability to predict the physical environment future by continuously adapting to operational changes based on information and online data collection from the physical environment. Therefore, it can be considered that a DT platform includes the integration of systems from data sources and data sets formed or supported by embedded sensors, wireless sensor networks, data, and digitized lifecycle systems integration with other cloud services and data providers [65]. Data is collected in real time to constantly adapt to changes in the environment or operation and provide the best results on the platform DT. This can be easily achieved by leveraging the significant advances in sensor design and manufacturing to synchronize the DT platform with the information collection from the physical environment. These sensors receive the information instantaneously and transmit it to the online plotter, continuously activating the virtual modes capability. Based on this, the DT platforms can be considered as three parts; a) physical product, b) virtual product, and c) communication infrastructure and information collection [66].

2.3. *Society digitally*

Technological change has greatly transformed the industry in the last 20 years. In recent years, dramatic technological growth has transformed industrial, economic, and social sectors worldwide. As a first step, the global connection to the "Internet network" [4] and the innovative and global economic startup models in the form of websites and platforms have profoundly changed all areas of human society. The spread of the internet in academia, the military, business, and civil society has been fuelled by the communication and decision-making tools and development capabilities of the Internet. In addition, internet services for sharing data over the internet based on search services, data downloading, and data discovery have been transformed from a local/regional to a global scale. These environmental and space advances can be valuable examples of SDI. This data infrastructure has achieved significant interoperability in advancing metadata and standardizing data encoding.

Although it has semantic limitations, pragmatic and contextual interactions that ultimately and non-technical interoperability issues such as data policy, openness level, ownership, and appropriateness hinder widespread use, the approach demonstrates. The interactions between digital worlds are completing day by day with the digital transformation advent: this perfect degree can be seen in economic, industrial, and social relations. This is exactly where stakeholders are involved and can approach the knowledge generation about group goals. On the other hand, to interactive services and tools, analysis and interpretation tools and services are offered, enabled by virtualization technologies such as local, regional, and global platform scales and cloud infrastructures. These capabilities are increasingly intertwined with common physical entities and processes in the "cyber-physical" [67] world.

In the "cyber-physical" world, the ability to collaborate among stakeholders has been moved to a higher level of data sharing and observation, i.e., to the information sharing level and knowledge generation from the data and data-sets analysis. The data produced hourly and daily by digital communities for stakeholders is so large and voluminous that it sometimes cannot be analyzed locally, effectively, and sustainably. It is up to the "cyber-physical" world to collect and analyze BD to generate knowledge. Therefore, transforming all aspects of our life into quantitative data [68] can be considered as an essential and relevant paradigm of data generation. The main task of the paradigm can be considered as the practical information production and is primarily based on three digital processes [69], as shown of Fig. 2:

a) *BD Collection:* It can be assumed that humans, machines, and natural objects create digital footprints that are connected into a knowledge network, including the collection, aggregation, and anchoring of digital artefacts. This digital environmental effort leads to what is known as "BD production." In this context, metadata-based data centres can be seen as very useful. Sources for collecting and updating BD include social networks, public administration, and e-commerce practises, the IoT, and new generation remote sensing tools.
b) *Deep Insights:* collected data macro-analysis using applied and comprehensive insights detection. This knowledge of applied and comprehensive insights is typically obtained using advanced analytics techniques using large datasets/semi/unstructured data sources of terabyte/zetabyte size. These methods primarily use advanced data management systems and machine learning models.
c) *Interpretation of actionable information:* Design, test, develop, and produce practical information; The profile development information design is based on the "end and gold" user's needs. This is achieved through specialised platforms that interact closely with users and shareholders.

According to studies [69], these two complementary paradigms used to study global change and sustainable development have led to the emergence of a new scientific model in collaboration with a large number of disciplines such as natural sciences, social sciences and humanities with interdisciplinary knowledge. This innovative and new field is called "Big Data Science (BDS)". To study the natural and social phenomena that characterise the Earth system BDS [69], a group of organisms is considered that includes local/national/global changes that affect natural cycles and the deep subsurface.

The main goal of the BDS field can be considered as a systematic, modelling, and implementing process understanding to generate data information and provide engineers, scientists, and decision makers with the knowledge needed in our society. The paradigms of data generation and knowledge information sharing are one step ahead in second-generation IoT platforms [70] the DT development on Earth by combining BDS science [71]. This is even though the IoT emergence has significantly expanded remote sensing and IoT sensors enable capabilities such as "fast and cheap access" to data and dataset deployed by billions of interconnected devices worldwide.

2.4. Earth digital twins

DTs reflect the industrial, scientific, and standardisation sectors in different definitions [72]. According to El Saddik [73], a DT can be considered as a "digital example of a living or non-living physical entity". The data is integrated and homogeneous, which creates a bridge between the physical and virtual worlds. A DT allows virtual beings to coexist with the desired physical being. A DT concept can be viewed as separating a digital system from its physical existence, making it easier to change the digital system without making other changes. A DT will also allow advanced modelling techniques to be used to create topics that are not possible with traditional models [71].

DTs cannot be called a new topic since they have existed in industrial processes for decades, but with the DTs proliferation, more and more are being introduced between social domains, and the most advanced models are designed for the interaction between the physical and digital worlds [74]. Moreover, the above can be considered as an overlap for the scientific departments involved in understanding and managing the global change impact. DTs have made it possible for the first time to imagine a digital version of the processes on our planet. This envisioning has been made possible by simulating and predicting their behaviour using large amounts of environmental data available with the AI technology advancement. Therefore, more efforts need to be made by all stakeholders to optimize data, interact with modelling platforms, and improve modelling techniques [75]. Four major challenges need to be fully addressed to develop the DT capabilities: a) standardisation of models and data, b) sharing of models and data, c) innovation of community services, and d) sharing of knowledge and researchers.

Today, various terms such as "*DTs of the Earth*" or "*Earth DT*" are used by EO societies [71], space agencies [76], climate research [77], digital Earth [78], and meteorology [24]. DT Earth is a digital copy of a component, structure, process, or phenomenon of the Earth system that connects digital modeling to reality, using different aspects from each community. A DT should be viewed as a live digital simulation that can be updated and whose changes can be monitored as its physical counterpart changes. Therefore, a DT can train from the ground and update itself continuously and simultaneously with in-situ/on-site and satellite remote sensing data and datasets. A transitional green society needs to undergo a digital transformation, which can be considered as one of the essential components to achieve sustainability. DTs in the renewable energy field are very useful to facilitate the simulation and physical implementation and further development cyber design tools.

3. Marine energy digitalization review

This section provides the ocean energy framework DT overview, the technological knowledge framework, and the modelling scope based.

3.1. Artificial Intelligence-based DT in systems

AI-based DTs in renewable energy systems recent advances in AI-based models, particularly ML and DL methods, are providing new insights into solving the complex renewable energy systems challenges. The main challenge in developing accurate online forecasts for

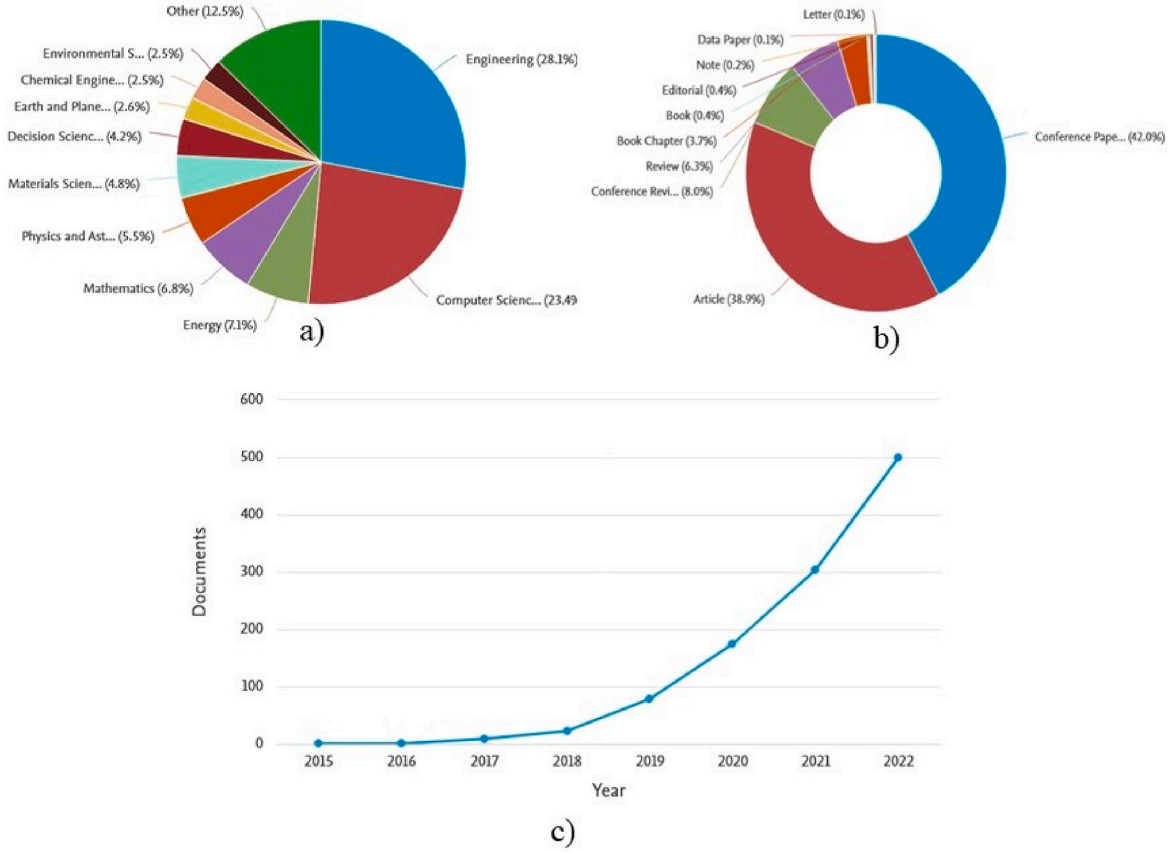


Fig. 3. The statistical and distribution of SCOPUS publications for hybrid AI-based and DTs' platforms between 2015 and 2022. (a) The various scientific percentage contribution fields in hybrid models. (b) The hybrid models distribution based on the types of reports. (c) The publications total number in the field of DTs combined with AI.

renewable energy systems is dealing with a high degree of nonlinear and large-scale time-series data that form a complicated pattern to propose a robust model with a high degree of generalisation [79]. On the other hand, evaluating the renewable energy systems performance in real scenarios is time-consuming and expensive. Digitization of the energy industry using DT techniques promises significant advances in managing and optimising costs and performance, providing timely maintenance services, improving energy efficiency, and developing existing sites [80].

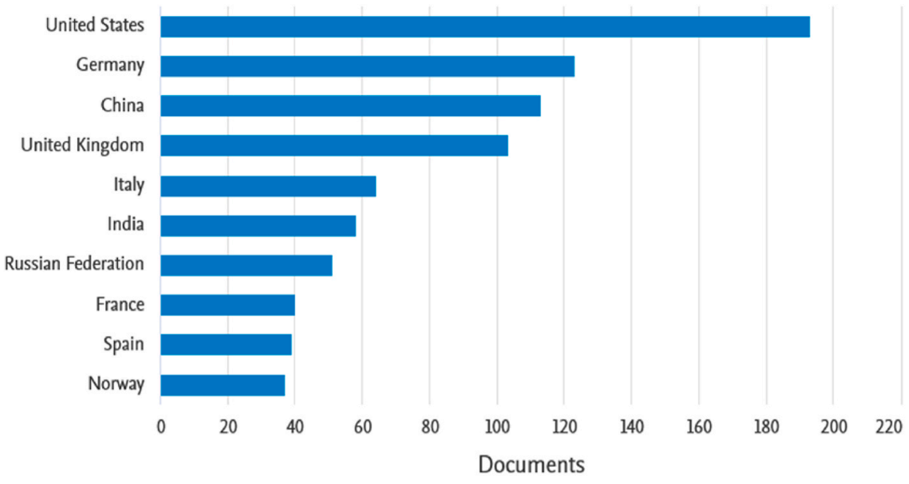
Developing a virtual model to simulate real-world problems is very time consuming and requires expensive computational resources [81]. An effective strategy to overcome these challenges is to use DTs in combination with surrogate models [82]. To increase the adaptability and generalizability of these simulations, learning strategies such as machine learning [83], DL [84], reinforcement learning [85], etc. play an important role. A combination of DT and intelligent system platforms enables more reliable and accurate performance in noisy, multimodal, and nonconvex systems. Fig. 3 shows the statistical results of this hybridization of AI-based, and DTs based on SCOPUS publications between 2008 and 2022.

As expected, this figure shows that the largest percentage of AI-based DTs is used in solving engineering problems (28.1 %). Computer science could take the second place with 23.4 % of the total applications. It is clear to see that the energy sector could only accommodate 7.1 % of these newly emerged hybrid model applications. Regarding the publications type, the conferences and journals shares are almost the same, 38.9 % and 42.0 %, respectively (Fig. 3(b)). Finally, Fig. 3(c) shows that the number of AI-based hybrid models for DTs has increased dramatically from 10 to 500 publications in the last seven years.

From Fig. 4(a), the most publications of this hybridisation come from three countries: United States, Germany, and China by 194, 123, 95, respectively, from 2015 to 2022 based on the SCOPUS database. Moreover, the National Natural Science Foundation was placed in the first rank in terms of publication number in this field (Fig. 4 (b)).

One of the most important types of renewable energy is solar energy because it requires low maintenance costs compared to wave and wind generators, and the installation panels are cheap and simple [86]. Moreover, it can be suitably connected to the power grid. Solar energy prediction is crucial for the development of a robust and reliable power grid; however, due to meteorological factors [87] such as clouds, rain, fog, air pollution, storms, etc., solar energy prediction faces several challenges. For hybrid solar energy systems (such as, agrophotovoltaic systems), since the solar power flow is dynamic and should be calculated iteratively to make an intelligent decision with the highest efficiency, a combination of ML models and the small virtual dimension [88] of solar energy can provide more accurate and faster prediction results.

Also, Zohdi [88] proposed a hybrid DT physical reality framework to model and optimize the discharge of solar energy, which has various configurations ranging from multi-panel preference, dimensions, bodies, primes, setting refraction effects, and so on. A recent study [89], proposed an advanced hybrid model that includes a Bat Optimization Algorithm (BOA) for managing the operational cost of the network and a Sequential Hypothesis Testing approach (SHT) to intercept identity-based cyberattacks and develop a secure and more predictable hybrid solar energy in real time. The result of the study [89] shows that a combination of the DT techniques with an optimization and learning strategy can perform better than the classical AI-based models in terms of feasibility and efficiency. Recently, the applications of DT for detecting and dealing with cyberattacks have been expanded, especially in hybrid renewables and smart grids.



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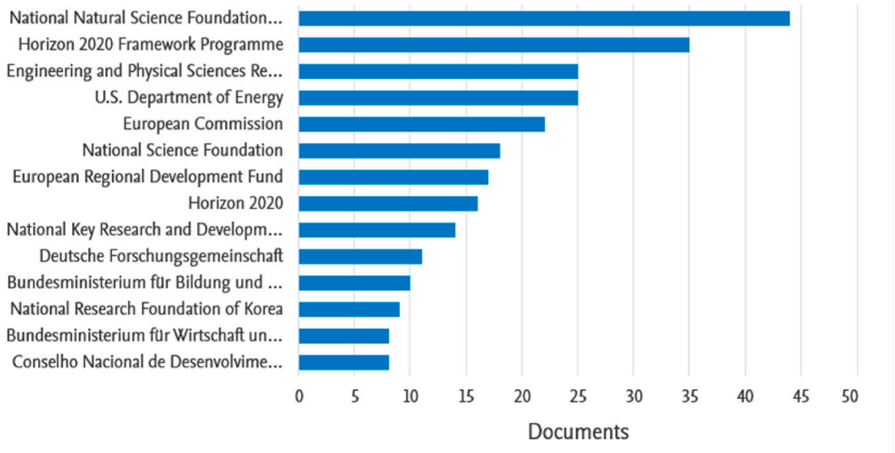

b)

Fig. 4. The statistical contribution of countries (a) and research institutes (b) in the field of hybrid AI-based DTs' publications between 2015 and 2022 based on the SCOPUS publications.

For example, Shen et al. [90] proposed a hybrid ML method to detect the impact of a Data Integrity Attack (DIA) on the performance of hybrid microgrid energy systems. To improve the utilization of wind turbine for regional consumption and increase the utilization of battery during peak hours, multi-criteria decisions by individual users play an important role. In another recent work, a reinforcement learning based framework was proposed [91] to model in DT to choose the optimal battery estimates based on wind power and photovoltaic availability predictions. The achievements of this reference [91] lead to the better understanding of user-level battery scheduling depending on different times and factors of the environment, and also improving the management capability with respect to the uncertainty of the environment. A wide range of tools have been used to maximize energy efficiency in buildings in the context of smart city development [92], including single and multi-objective optimization methods [93], machine and DL techniques [94], mathematical modelling [95], and recently DTs [96].

The development of efficient energy systems for buildings plays a crucial role to improve the contribution of dynamic renewable energy in smart cities,. For example, Silva et al. [97] proposed a hybrid real-time model composed of ML, DT, and experience-based information to collaborate with the real energy system to maximize energy efficiency in buildings. The proposed hybrid model provides high flexibility and more automation for various dependent components of energy and sustainability systems and gives a clear insight into new dimensions related to autonomous smart energy management systems.

However, the application of modern ML can provide a more accurate predictive model than classical models. To estimate, model, manage, and optimize energy efficiency in residential buildings, Deena et al. [98] developed a combination of the Naïve Bayes classification method with the IoT based on 216 apartments in Rome, where 70 % of the consumed electricity comes from renewable sources. The modeling results showed that real-time monitoring DT could improve energy efficiency and more sophisticated energy control plans could be designed. The same case study in the city of Rome [99] was used by Agostinelli et al. to evaluate the impact of the AI-based model combined with DT in modeling energy efficiency in buildings. Moreover, a combination of machine learning and DTs can be used for long-term power load planning of renewable energy systems, e.g., day-ahead [100].

One of the surrogate modelling DT considerable advantages is that it saves a large portion of the computational budget compared to traditional simulators. Increasing the number of systematic input parameters forces huge simulator computations; therefore, lightweight DT can outperform direct simulations. The ML and AI-based methods are used due to their high learning ability to reduce the simulation error. In fact,

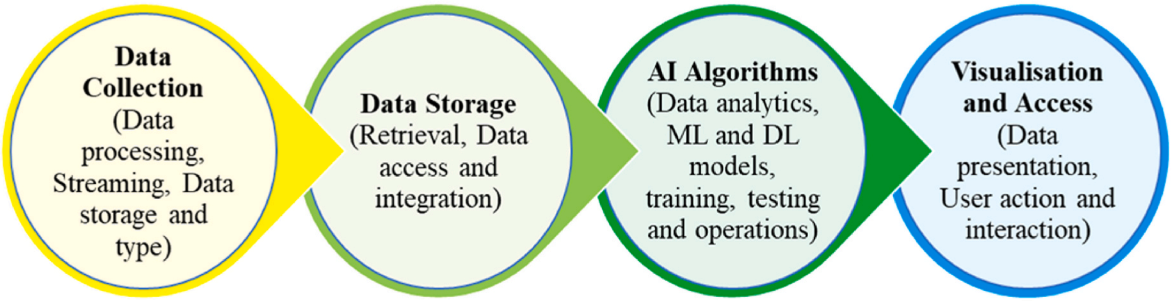

Fig. 5. DT data ecosystem.

the DTs model performance strongly depends on an appropriate training process. In recent years, several studies have focused on intelligent systems ability and application to improve the digital surrogate models efficiency [82,101].

The training process depends on the domain of the surrogate model: local or global [102]. For local surrogate model development, supervised or unsupervised regression methods and Response Surface Methodology (RSM) are used [103]. However, for global digital surrogate models, more robust models with high generalisation potential are needed, e.g., fuzzy logic [104], artificial neural networks, DL, transfer learning, kriging models, etc. [105]. Meanwhile, reliability and trustworthiness are the main concerns of designers in implementing and applying DTs and surrogate models in real-world sensitive and safety/mission critical problems. Therefore, there are several techniques to deal with this uncertainty, such as landscape and sensitivity analysis, AI-based Uncertainty Quantification (UQ), etc.

One of the basic components of the platforms of DT are virtual sensors to collect and analyze the technical and geometrical information of the structures in renewable energy systems. The finite element methods and aeroelastic models are used to develop an initial version of the surrogate model with high accuracy to predict various features such as wind speed and power, direction, air temperature, and yaw angle using the collected Supervisory Control and Data Acquisition (SCADA) datasets [106]. To support intelligent monitoring planning, predictive maintenance of wind farm functions, fault diagnosis, and condition monitoring, the observations are the regions under the guidance for elementary analysis and the latest technology enhancement incorporated into the DT frameworks [107].

3.2. The DT energy framework

Earth's DTs concept is at the ambitious creativity and innovation initiative heart of European Countries (ECs) known as DestinE [108]. This creative initiative has been integrated into the European strategy as a concrete step towards the common European space data and dataset realization [109]. Furthermore, the Green Deal [109] was launched to harness the BD potential to support priority actions in the climate change, circular economy, zero pollution, biodiversity, and deforestation areas.

In this context, in-situ, on-site, and satellite remote sensing observations and sensors are accessed in a comprehensive database with different time-series resolutions for automatic analysis by AI, ML, and DL algorithms (Fig. 5). The system provides a digital platform for visualizing, monitoring, and predicting activities on Earth in support of sustainable development, and thus in support of efforts to improve the environment as defined in the Green Deal.

The EU digital strategy is [110] based on ethics, democracy, fairness and open independence. In this respect, Copernicus remote sensing data streams will help to form the digital core. The digitization project aims to create a dynamic, interactive, multidimensional, and intensive system replica that allows public, scientific, and private "gold user" and "end user" groups to interact with the Earth at scale. In this case, natural, social, and economic information can be viewed as a common infrastructure that provides access to data, advanced high-performance computing, software, and applications. This infrastructure is then made available to various DTs that replicate different aspects of land and ocean systems, such as climate and climate change prediction, global ocean circulation, food and water security, and ocean biogeochemistry [108].

An SDG knowledge framework must address critical technological challenges and constraints, including multidisciplinary and component heterogeneity and a high degree of long-term evolution. DT has identified the following fundamental requirements to address these challenges: Providing a cloud-based platform that allows users to access highly heterogeneous data, analytics software that consists of heterogeneous processes and modeling algorithms, and is based on data services and a dashboard tool. User types must be able to access and interact at different levels of complexity with models, scenarios, services, and predictions to support usage development. Therefore, DTs visualizations should be considered as vertical digital components connected to a leading platform that provides common horizontal and scalable capacity services. The DTs requirements and limitations are based on a policy-based analysis [111] and a review of similar DT systems at national and international levels [71]. Three priority areas were identified in this section: a) Risk management of severe natural disasters due to climate change, b) Climate adaptation and security in water and food supply, c) and Energy digitalization.

The DT architecture [112] based on use requirements and constraints, is also necessary to address the SDG agenda using existing and heterogeneous systems in the proposed knowledge framework. In addition, the proposed knowledge framework must address evolving and changing policy challenges. This needs to change by designing and developing more and more DTs to evolve with new data, actors, etc. The proposed architecture applies to the digital paradigm for the reasons stated above. A decade of experience has been gained in the Global Earth Observation System of System (GEOSS) infrastructure development, which can be very effective based on the System-of-Systems (SoS) bottom-up approach. The GEOSS infrastructure has been operational since 2015 [113], and was developed based on the Global Earth Observation (GEO) community changing needs.

3.3. Technological knowledge framework

The digitization paradigm can best accommodate evolving systems, such as GEOSS and the Earth digitization. The natural ecosystems introduced the biology concept [114], which can focus the ecosystem paradigm on a holistic view of diverse and autonomous living things as the "biological" typical environment and the "non-biological" component. This system interacts and evolves to pursue benefits, developing and modifying new competitive or participatory strategies. The digitization approach allows capturing the evolutionary system process of DTs and SoS requirements such as GEOSS or SDG knowledge frameworks for more sustainability. An overview defines the digitization pattern and can identify the need for different actors and expertise, shift the focus to communication [115], and focus on the ability to achieve expected outcomes over time [116].

While shared interests in software digitalization are critical to the technology's evolution and survival, the stakeholder's common interests should be the data chain value design and operation. Thus, a successful DT can be a prominent feature of a data-driven stakeholders economy, cloud service providers companies, investors and entrepreneurs, research institutes and universities [117]. The DT development can contribute by bringing together stakeholders and directing financial sources that facilitate stakeholder cooperation in the data economic landscape. A DT can be activated by three underlying conditions under which stakeholders operate in the ecosystem actions as providers, intermediaries and consumers [118,119]; they determine and formulate laws, policies and standards that affect how the ecosystem components are structured and interact. Firstly, identifying shared social and cultural values affects the stakeholder's organizational structure [120], Secondly, these values drive the ecosystem stakeholder forward behaviour [121]. Thirdly, provide storage conditions for data, analytics software, network elements, and communication instructions connecting these elements to network operators and users [119].

The engineering and technology framework uses microservices and Application Programming Interface (API) technologies to implement flexible interoperability between software components. This flexible interoperability framework fully supports flexibility features, modularity, and scalability. Virtual cloud layers virtualize operating infrastructures in a multi-cloud environment by implementing the necessary mediation services and publishing a set of open, shared, and compatible network services and related APIs for clients. The ecosystem's organizational components remain substantially independent and evolve freely over time. Virtual cloud services allow the multi-cloud infrastructure, preventing the changes and customer plans to release. These new operational infrastructures can be added transparently to enrich ecosystems. Their needs and limitations affect the framework's different service layers. Thus, the more layers are separated, the more stakeholder concerns diverge, and the computer science model of "concerns separation" is used [122].

Satellite remote sensing distributed extensive data and datasets in the series age and solutions movement, and the analytics software movement around ecosystems should be minimized as much as possible. The metadata-sharing system and microservices must be precisely managed to implement a practical and useable distributed data system. Given the multidisciplinary scope specified in DT and the data set resulting in high heterogeneity to be processed, data intermediation and intermediation services with their APIs should be developed [123]. It is crucial to fully understand the interoperability implemented level by that software in learning-based AI models for satellite remote sensing in which analytical software is the primary mobility source in a distributed system [124].

4. A Thriving Marine DT: Principles and Patterns

A set of system design principles, patterns and related software must be properly applied in the architectural framework design [121] and implementation for the DT's successful design [125]. Those steps can be classified into the following four sections.

4.1. Evolutionary development of a marine DT

The marine DT's first condition is its flexibility and dynamism. This dynamic experience can be adequately understood in the GEOSS case. A flexible marine DT operates in an environment where technology and policies must evolve and grow. Given these architectural features, it should implement high flexibility to functionally separate infrastructure and platform (SoS) systems from applications implemented via DTs.

In this case, the goal is to implement a highly scalable system with the features capable to achieve the shareholders' business goals and objectives. Furthermore, the industrial competition guarantees and the independence values characterising the local area or the area where marine DT operates must add to social values. The above principles underlie the proposed architecture for the DT's successful integration to develop as an independent and free digitalization [126].

4.2. Marine DT behaviour

Marine DT can work effectively when there is a different and higher value for the species of its members that they create without being part of platforms. This increase in the member genes value can occur independently due to an unpredictable interaction. This situation can be rightly seen in natural ecosystems. In this case, it is well known that destructive changes can reduce the ecosystem dynamics balance and change it in the wrong direction. Therefore, common normative and managerial interventions must be applied appropriately and developed to maintain the natural ecosystem's increasing value to human society. The marine DT creates knowledge value production and shares social and human challenges by interacting among member species unpredictably.

Respectful planning and management are essential to respect and maintain the desired capabilities, thus preserving the marine DT's social values in design. The following aspects should be considered as primary factors, i) a marine DT is based on a paradox of independent and participatory institutions. This means that organizational systems reduce their independence to accurate levels of risks and cooperate [127], ii) establish shared values concerning organizational value for the marine DT effectiveness to protect the participating organizational systems. The protection type allows users to maintain independence and diversity. It allows common values to emerge, iii) use standard components built on the organisation's infrastructure that can save and develop at different scales using standard technologies, waste effort, and sources widely accepted and prevent duplication. In addition, partnerships between the sectors can help reduce costs and exploit innovation from a broader shareholder base.

4.3. Marine DTs systems geographical distribution heterogeneity

The marine DTs design and development main challenge can be considered as “Big Data” challenges that require appropriate strategies to manage the volume, speed, diversity and data value sources [114]. Another challenging part is network computing, such as controlling and managing input and output for metadata. Minimizing data movement, repetition, time-lapse analysis, and energy will be very effective. Digital converter technologies introduce the continuous computing concept [128]. During the paradigm implementation, programs can form part of their logic on different infrastructures to minimize latency and energy consumption [129]. This paradigm requires a holistic distributed system abstraction that allows lightweight microservices to be deployed on IoT platforms with limited network sources with more sophisticated microservices running in large-scale data centres [130]. Significant differences between traditional and engineering systems make DT more pronounced.

The engineering system aims to optimize the performance in question [131]. Optimization in system performance is a novelty developed by economist Herbert A. Simon [132], describes a decision-making strategy to find a satisfactory rather than an optimal solution [133]. However, it should be expected that these strategies can be costly and time-consuming for complex environments [134], such as marine environments. Therefore, marine DT design is a typical architectural process in a multi-criterion, the multi-objective context that faces the most logical approach to choosing the same challenge to find the optimal solution or accept a satisfactory solution.

A marine DT will be built on the block's foundation called the enterprise systems. Therefore, creating elements to fill potential gaps and realize a complex SoS super-system will be stimulated [135]. These

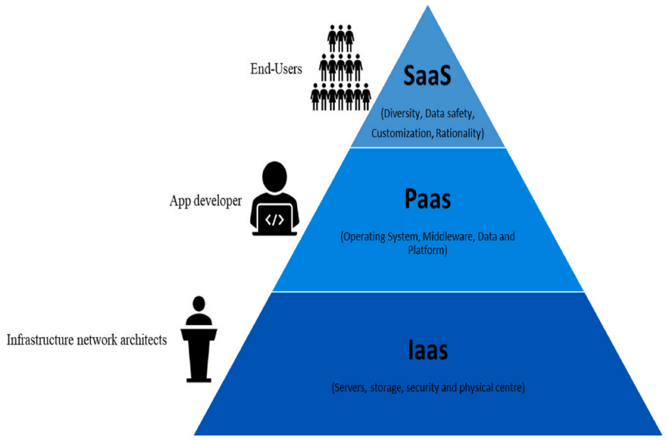

Fig. 6. Show multi-cloud approaches of infrastructure, platforms, or software combination services.

blocks are very heterogeneous in marine DT to support environmental policies. In this case, designers can refer to the old systems' goals, technological features and content managed by different organizations. Therefore, it can be said that the marine DT's success will depend more on how the marine ecosystem is properly managed. Given these marine DT ecosystem characteristics, SoS management different styles are considered [126], which include management configurations that are fully distributed [136] or fully centralized [137].

5. Marine DT mechanism

The marine DT is constantly exposed to widespread change for reasons such as organizational system changes, new systems addition, and changes in the social and technological environment. These changes must be considered in thinking of DTs as they can be very destructive and make it impossible to continue providing services for the target community's benefit. Hence, a marine DT needs to detect and respond to changes thoughtfully [138]. A marine DT constructive mechanism will be available when a shared social value identifies choices for organizational systems to meet organizational utility in an overall interaction [127].

A marine DT must be able to support all the diverse and evolving aspects that each organization decides. These compromises define the component systems' whole nature and can evolve further [139]. However, it should not be forgotten that all aspects discussed mainly relate to the governance sphere. First, transform the marine DT system strategy into a stable system over time that has the power to maintain itself [140]. A marine DT must be seen as a set of parts that must be dynamically and carefully controlled. Achieving this goal can be achieved by developing effective communication and control functions.

Therefore a cybernetic system must be implemented to maintain the marine DT dynamics [141], including specific components required for communication and control functions [142]. Organizational systems will operate at the first-level operation level in a marine DT, which will operate at the second level to control SoS evolution and deal with conflicting elements [143]. A marine DT is expected to share a range of core digital entities with activation services. The core digital has main parts, including, a) political and business organizations, b) the framework structure organizing, software and user dashboards, c) constituent infrastructure organizations and shareholders.

A successful maritime DT will support the following conceptual, digital and virtual entities; DTs can be identified as programs that the ecosystem will support, which can better address the climate change risks, climate adaptation, food security, digital oceans, including food and environmental pollution, manage environmental protection and marine renewable energy [111]. The data streams should be considered for digital insights that properly develop commercialization and customer orientation to support digitalization issues [144].

A digital string can be defined as a record of the entity's life and the system covered from the time of its design (birth) to its cancellation

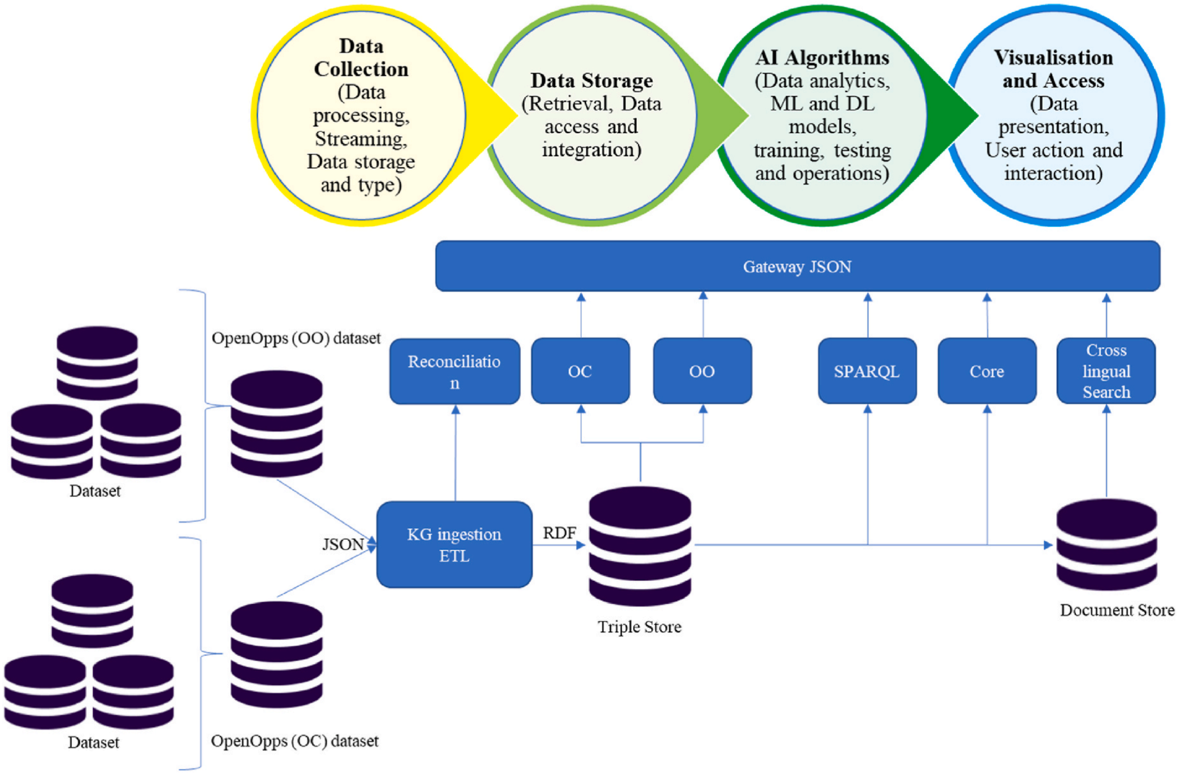

Fig. 7. Shows a DT architected components as an editable example.

Table 1
DT projects as best practices around the world [155,156].

No.	Project Name	Aims	Project Summary	Sector
1	SHELL, RWE AND AKSELOS TETRASPAR	Shell and RWE commissioned Akselos to model the TetraSpar floating wind foundation demonstrator using Integra® structural simulation software, in the Norway coast.	The TetraSpar demo project developed by Stiesdal Offshore Technology, TEPCO Renewable Power, Shell, and RWE. The project installed 13 km offshore at the Marine Energy Test Centre near Stavanger in southeastern Norway. Akselos' software will help accelerate the demonstration of the industrialised offshore foundation. The goal of the TetraSpar project is to drastically reduce the cost of electricity for floating wind farms.	Offshore Wind
2	NEPTUNE ENERGY, L10 AREA CCS DEVELOPMENT	The DT project aims to speed up workflows and reduce costs and environmental impacts by allowing engineers to work on land and support the carbon capture and storage project design, which has the potential to shop 120–150 million tonnes of CO_2 safely.	Neptune Energy is working on the DTs development for the large-scale carbon capture project in the L10 area in the Dutch North Sea.	large-scale Carbon Capture and Storage (CCS) project
3	GAZPROM NEFT, ALEXANDER ZHAGRIN FIELD	The Alexander Zhagrin field is an essential component of an oil cluster being developed in the Khanty-Mansi Autonomous Region, Yugra. This is Gazprom Neft's fastest-developing project, with an estimated resource potential of more than 840 million tonnes. The Alexander Zhagrin field was discovered in 2017 and entered commercial development in 2019. The field is now equipped with cluster pads, oil recovery pipelines, a separation plant, the first power plant complex, power supply lines and road transport infrastructure. Construction of the oil transportation infrastructure is nearing completion. The millionth tonne of liquid hydrocarbon was produced in 2020. Peak production of 6.5 million tonnes of oil annually is expected to reach in 2024.	Gazprom Neft has developed an integrated, holistic model for one of the company's most promising assets, the Alexander Zhagrin field, in the Kondinsky district of the Khanty-Mansi Autonomous Area Okrug, Yugra.	UPSTREAM
4	SHELL, ORMEN LANGE GAS FIELD	The first version of Ormen Lange's DT mainly involves data integration and visualization of 3D subsea models, including production and MEG pipelines, locations and drilling paths, seabed bathymetry data around production templates, documentation, and drawings, and real-time DCS data. For subsea maintenance, wells, flow assurance, production engineering, reservoir engineering, process engineering and operations, the twin provides consistent data that all can access. In addition, Norske Shell intends to extend the development to specific use cases to enable new ways of working for its user groups,	Norske Shell uses Kongsberg Digital's Kogni twin Energy solution to visually represent the Ormen Lange deepwater gas in the Norwegian Sea.	RESERVOIR-TO-MARKET

(continued on next page)

Table 1 (*continued*)

No.	Project Name	Aims	Project Summary	Sector
		disciplines, and teams.		
5	BW LNG, BW MAGNA	A pilot project has been launched to develop and test a maritime DT to promote operational excellence, reduce emissions and costs, and improve safety. The maritime DT is being developed for BW Magna FSRU and leverages Vessel Insight's data infrastructure, Kognifai's digital platform and Kongsberg Digital's maritime simulators, and Alpha Ori's value-added expert applications. The pilot project is intended to provide an example of the benefits of digitalization for the industry.	Kongsberg Digital, BW LNG, and Alpha Ori Technologies have signed a strategic digitalization partnership to increase the efficiency and reduce the LNG carrier's (LNGCs) environmental impact, floating storage, and regasification units (FRSUs). The agreement covers several projects, including using a common data management platform and developing maritime DT and digital processing models to facilitate operational excellence.	SHIPPING and MARITIME
6	VÅR ENERGI, WEST PHOENIX RIG	Sensor data collected by remotely operated submersibles is analyzed by 4Subsea's 4 insight digital service, which presents easy-to-interpret insights and dashboards to support critical decisions.	Norwegian company 4Subsea has signed a three-year contract with Vår Energi to monitor and analyze wellhead integrity during drilling and completion operations for Balder Future using the West Phoenix rig.	UPSTREAM
7	AKER BP	Aker BP has signed a contract with FutureOn to digitize their workflows using the company's DT software. The contract will run until April and will involve the use of FutureOn's field design applications, API-centric collaboration platforms and DT technology to aid in the visualization of subsea data, mapping of DT field design, and fostering better digital collaboration between engineering and project management disciplines during the subsea field development phase.	Aker BP has entered into a contract with FutureOn, a software company based in Oslo that specializes in providing digital solutions for oil fields, to provide software solutions that support field development operations.	UPSTREAM

(death) [145]. Hence, the digital discipline concept is essential for imagining, implementing, and re-analyzing the DT design and development. In this regard, virtual network services will provide the ability to provide appropriate performance on cloud-based virtual machines in a network service environment or default virtual machines. Furthermore, the ecosystem network simplification will allow data collection from distant and different sources suitably and practically.

The DTs engineering paradigms, models, and interoperability technology reference frameworks must be considered for providers' successful implementation [146]. Multi-cloud approaches refer to more than one cloud by providers [145]. These multi-cloud approaches can be a combination of infrastructure, platforms or software as different services (Fig. 6) such as, Infrastructure as a Service (IaaS), Platform as a Service (PaaS), or Software as a Service (SaaS) [147]. In multi-cloud approaches, private and hybrid clouds with several components are practical and common. Implementing a virtual cloud template, a multi-cloud approach to provide a rich user experience [148], is efficient. More than 90 % of the organizations surveyed use more than one cloud infrastructure according to an international survey on cloud usage [149,150]. Therefore, organizations and applications can increase their efficiency and effectiveness for each use by applying strategy [151].

In this regard, users interact using a multi-cloud DT platform based on a virtual cloud. Due to the cloud's unique infrastructure and management needs, data centres can be considered as extensive facilities in a limited number of places. In this case, customers and users are usually away from the cloud data centres managed by providers. Edge [152] or fog computing infrastructures are likely closer to those devices and applications to provide computing capacity with less response time [153]. These computations can be efficient for long/medium/short-term scenarios, while the cloud centre effectively supports unrealistic and long-term data-driven scenarios [154].

6. Virtual Cloud Layers and Services

Virtual cloud services using a layer such as IaaS, PaaS, and SaaS allows users to utilize a distributed cloud solution dynamically and with a transparent method for users. The virtual cloud service layer complies with the accepted flexibility requirements for a DT. A virtual cloud orchestration uses software tools to manage connections between the systems that comprise a multi-cloud infrastructure. Orchestration leads to a set of virtual machines that provide the sources needed to implement the scalability and availability of requested services. In DT, virtual cloud orchestration should be tested, designed, and developed to allow highly facilitated evolution in SoS. In agreement with the possible DT government styles, which implement a centralized or distributed network approach, quantitative orchestration architectures can implement ecosystem technology [126].

Fig. 7, show the DT architecture components as an example.

7. DT platform launching

In the table below, the DT projects examined examples in offshore marine sectors. These studies are summarized in different sections in

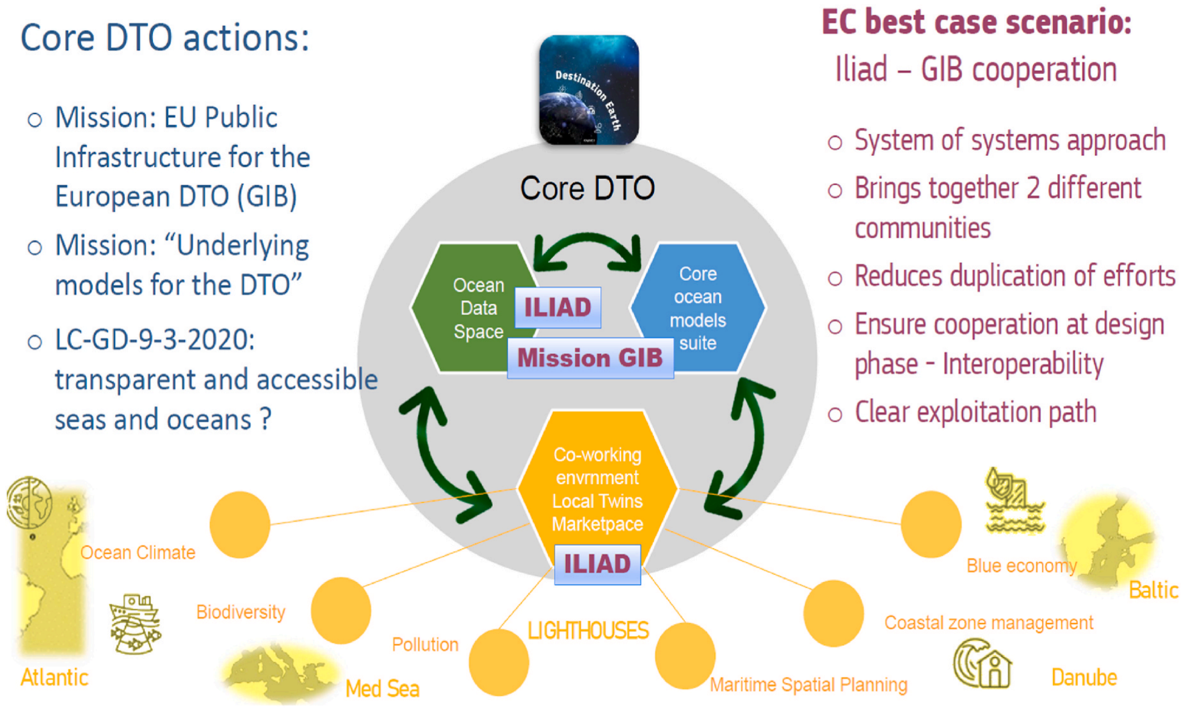

Fig. 8. ILIAD DTO core [157].

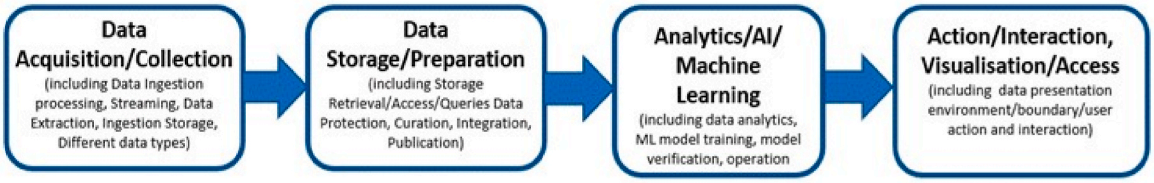

Fig. 9. ILIAD pipeline architecture steps [157].

Table 1.

7.1. ILIAD as a Best Workout

The main objective of the ILIAD project [157] is to develop, operate and showcase a set of DTs of the Ocean (DTOs) which will support the design, development and operation of innovative services related to oceans and seas. ILIAD aims to develop, operate, and demonstrate an interoperable, data-intensive, and cost-effective DTO that leverages the vast amount of data provided by various Earth Observing sources, modern computing infrastructure, such as IoT, social networking, BD, cloud computing, etc. This DTO will be designed in an inclusive, virtual/augmented, and engaging fashion to tackle all the challenges related to Earth data.

ILIAD aims to combine high-resolution modelling with real-time sensing of ocean parameters, advanced algorithms for forecasting spatiotemporal events, and pattern recognition. The DTO will consist of several real-time to near-real-time digital replicas of the ocean. These DTs will support the intelligent and innovative services design and development, paving the way for an open, actionable, and equitable DT of the ocean throughout the EU and beyond, starting with the partner countries. The DTO is divided into 12 fields across eight European geographies, as illustrated in Fig. 8.

ILIAD DTO is a project that aims to develop and combine digital models of existing ocean assets. This will help in the creation of the water economy using the latest technology from Industry 4.0. The project will enable us to address all Earth data challenges with high-resolution modeling and real-time measurement of ocean parameters. Fig. 9 shows the DTO architecture, which is presented in four distinct pipeline stages. Each stage defines the architecture components that must be developed to serve all DTO use cases (see Fig. 10).

The first block, data collection/acquisition, is responsible for collecting data from various sources, including streaming and extracting data from related external data sources and data spaces, as receiving input data from sensors in real-time or offline. This block seamlessly integrates with various APIs of required input systems, as it can send files or messages in plain text format, complex text format, XML format, JSON format, JPEG format (or any standard image/common) and receives MPEG format. or any standard/common video format). Furthermore, it can also play text from blogs, social media posts, articles, and news feeds.

The second block, the data storage/preparation block is responsible for maintaining an appropriate data storage system and preparing and maintaining data for further use and processing. Its vision is broad, and it includes interoperability and the use of relevant data lakes. The block is responsible for implementing data interoperability with incoming data systems and data spaces, including the ILIAD data catalogue and service catalogue. Since this block performs the data transformation, it must complete all necessary transformations and normalizations before processing the analytical model. The block is also responsible for maintaining all metadata for ILIAD data, services, and models, and providing a market perspective for the data. Depending on the use case,

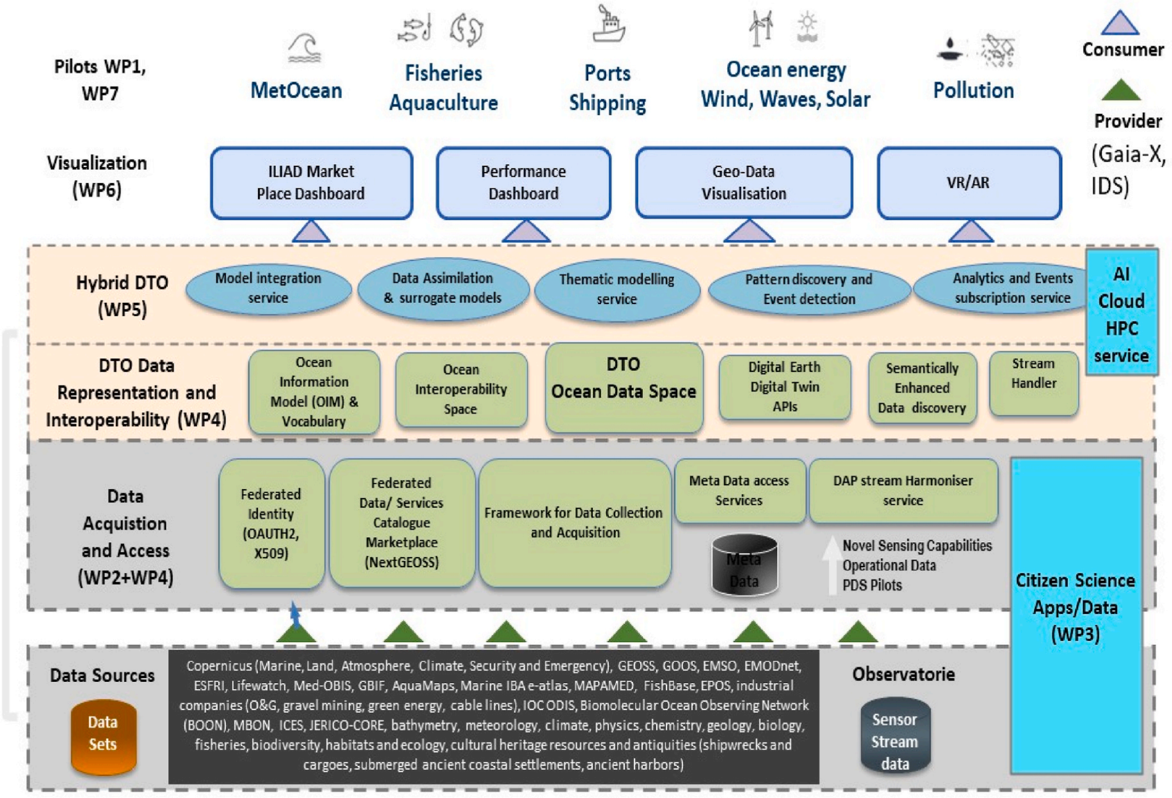

Fig. 10. A high-level view of the ILIAD architecture SoS [157].

it will necessarily be able to scale data transformation processes in real-time or in batches.

The third block, the field of analytics/learning methods incorporates various data analysis techniques such as descriptive, predictive, and prescriptive analysis, along with learning methods and algorithms that support decision-making and knowledge transfer. It also involves numerical modeling that is necessary before applying the methods. These methods can scale data transformation processes in real-time or batch, depending on the specific use case.

The fourth and last block, the visualization and access module is responsible for presenting data in an interactive way, allowing users to interact with the environment, and defining the boundaries for the actions. This is achieved through visual interfaces that use various data visualization techniques for human users, and through APIs or interactive interfaces for system boundaries. This involves providing access to interactive dashboards and a marketplace where users can acquire and expand subscriptions and ILIAD products and services on a pay-per-use basis. The team also handles user registration, user profiles, authentication and authorization, and payments.

The ILIAD approach is a SoS that aligns with the emerging European Data Spaces and the related ecosystem of interconnected data spaces from different perspectives such as INSPIRE Twin of Twins, GEOSS - SoS, and European Data Spaces. The technical perspective of the ILIAD approach is based on technology frameworks and collaborations of the Big Data Value Association (BDVA) and the emerging Public-Private Partnership (PPP). The BD and AI pipeline framework is built upon the elements of the BDVA reference model. A top-level generic pipeline has been introduced to provide an overall usage perspective on BD and AI systems to better understand the connections between the BD and AI systems in the application flow context.

8. Conclusions

It is time for humanity to face preserving Earth's unprecedented challenges and achieving more and more stable and just society. This is primarily a political challenge, requiring the support of a robust multi-disciplinary knowledge platform that can provide the scientific evidence needed by policymakers and EO-decision-makers. The covered site measurements to be operational for use in the DTs platform must go beyond the oldest data exchange interoperability model to use the updated information and knowledge sharing model, which can be considered as the "cyber-physical" world characteristic created by the societies digital transformation. This paradigm is activated by another innovative model called data generation, which uses practical information from time-generated data series.

This paper introduces the DT concept approach to curb digital transformation and develop the knowledge framework features needed for global change and the SDG agenda implementation. The framework is general and effectively supports the DT's production and use. DT marine and GEOSS were cited as examples to introduce the new approach to harnessing the digital transformation and developing characteristics of the framework needed for global change and implementing the SDG agenda. This paper discusses DT from various perspectives, including fundamental principles, patterns, and engineering architecture. In this regard, an exemplary process must first be designed; then, the influential technology must be identified. Such a human factor is also an essential factor that must be considered in all design and development stages. A DT is a new model for developing a knowledge system distributed among multiple stakeholders. In the developed DT, advanced digital strings for the DTs production and operation are essential to the Green Deal data space and must be implemented correctly and without human error.

The ILIAD project structure has been designed and developed to ensure interoperability with other EU and UN projects. In this project, the GAIA-X federated architecture and the Interactive Data Space (IDS) [155,156] are implemented to enable data federation with all systems in the EDITO ecosystem. Furthermore, a SoS approach has been chosen to implement the ILIAD DTO ecosystem. These data will serve as the starting point for each DT created by ILIAD and will also be used to determine which existing DTs to incorporate into ILIAD. The ILIAD novelties, are manifold [157]:

- The ILIAD system will interact with all existing data platforms, making it a Platform of Platforms, or SoS. The DTO will become a Twin of Twins.
- The ILIAD is a data-source model, AI model and sensor-agnostic.
- The ILIAD is an open SoS that can adapt to the emergence of new DTOs and evolving technologies. Iliad will adopt the best practices of the ocean community and contribute new practices to advance the field.
- In ILIAD, modeling capacities will significantly improve the spatial and temporal resolution of all digital representations. This will enhance the accuracy of digital representations.
- The ILIAD will address the full scope of data and information, including their values, uncertainties, and provenance. The system will consider state-of-the-art software development, verification, validation, and deployment methodologies at both the component and system levels.
- The ILIAD will involve users and stakeholders throughout the co-designing process. This is a multi-disciplinary approach that includes natural and social sciences, as well as business and policy considerations.
- The ILIAD will also accommodate new and emerging sensors and data sources, such as environmental DNA (eDNA) and ocean topography.

This implementation system can be managed with multiple data source input systems and many sensor data from different regions, a considerable amount of generated data. In this regard, a decentralized federal architecture is the best solution. It allows data to be operated close to the intended source, reducing the costs and risk of properly centralizing data. A data pipeline synchronization approach has been implemented with multiple standards and interoperable data pipelines to enable data processing and availability at the data service layer for application consumption. In addition, to maintain data interoperability, a data space approach has been implemented to allow the federated catalogue creation, an ocean vocabulary, and an ocean information model. In addition, through subscription, a marketplace offers verified users all the data in the data space, not just data but also applications.

Credit author statement

Meysam Majidi Nezhad: Conceptualization, Investigation, Methodology, Writing – original draft preparation, Resources, Validation, Data processing, Reviewing and Editing. Mehdi Neshat: Investigation, Data processing, Writing – original draft preparation, Resources, Visualization, Reviewing and Editing. Anders Avelin and Fredrik Wallin: Investigation, Visualization, Reviewing and Editing, Georgios Sylaios and Davide Astiaso Garcia: Methodology, Resources, Validation, Supervision and Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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