



Review

# Digital Twins for Research and Innovation in Support of the European Green Deal Data Space: A Systematic Review

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**Abstract:** According to the European Data Strategy established in 2020, the European Open Science Cloud (EOSC) is described as “the basis for a science, research and innovation data space. . . and will be connected and articulated with the sectoral data spaces”, being one of the 14 European Common Data Spaces. While current cross-sectoral interactions with the EOSC are realised through the association’s Health Data Task Force, advancements in other EU priorities, such as the Green Deal and the Digital Strategy, should be accelerated in the green and digital transitions and integrated by reinforcing each other to be climate-neutral by 2050. With this motivation, this paper systematically reviews data spaces and digital twins (DTs) within the context of research and innovation. Specifically, focusing on the relevance of the EOSC to the Green Deal Data Space (GDDS) and DTs of the Earth, the relationship between them is explored using a topic search with various keyword combinations in the Web of Science and CORDIS databases. Based on the selected scientific articles and projects, collaboration opportunities are mapped to connect relevant stakeholders. Furthermore, existing and developing service components that could contribute to technical building blocks for the GDDS are identified. In summary, key findings are highlighted, addressing the current gaps and opportunities among the GDDS initiatives presented in this review.

**Keywords:** European Green Deal; data spaces; European Open Science Cloud; digital twins; Destination Earth; digital transition



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## 1. Introduction

Over the past decade, digital twins (DTs) have received increasing attention in many scientific and engineering research domains [1,2]. Over the last few years, DTs that were initially used for industry-oriented projects have expanded their applications from manufacturing to healthcare, energy, and finally, the environmental sector [3]. At the same time, since 2014, the concept of Open Science and Open Innovation in Europe has evolved, stimulated by the European Commission, which launched the European Open Science Cloud (EOSC) in 2018 where research data can be safely stored and shared through a trusted and federated environment [4–6].

Subsequently, the European Strategy for Data was established by the European Commission in 2020 [7], which aims to generate a single market for data across sectors and countries, initially facilitated by nine Common Data Spaces (Industry, Green Deal, Mobility, Health, Financial, Energy, Agriculture, Public Administration, and Skills) as well as another five data spaces (EOSC, Cultural Heritage, Language, Media, and Tourism) [8]. To support the development of each data space and build their data infrastructures, the Digital Europe Programme (DIGITAL) [9] awarded Coordination Support and Action (CSA) projects for sectoral data spaces (e.g., GREAT project for Green Deal, AgriDataSpace project for Agriculture), while another funding action (the Horizon Europe Programme, HORIZON) was mobilised for research and innovation [10]. In addition, the collaboration and harmonisation across data spaces increased when the Data Space Support Centre (DSSC) became active in 2022 under the DIGITAL CSA project.

To tackle global challenges addressed in the EU missions and priorities [11], such as Climate Change Adaption, Cancer, Restore our Ocean and Waters, Climate-Neutral and Smart Cities, and Soil Deal, the solutions to those are often overarched across sectors and application domains in the digital decade to accelerate digitalization. Following this trend, the Joint Research Centre defined the goals of the European Green Deal as a starting point to examine the opportunities and challenges in the green and digital transitions [3,12]. Environmental monitoring is a key tool for achieving many of these goals, in particular, with DTs that can improve efficiency in simulation and prediction [3]. Thus, research ecosystems are required to leverage the development and improvement of green-digital technologies for the implementation of innovation infrastructures [3].

To date, there have been several review articles on DTs in the environmental sector focusing on agriculture [13–24] and Earth systems [25–31]. A few of them are also related to an emerging Green Deal Data Space (GDDS) [29,31]. However, so far, no review includes the EOSC as a mechanism to connect research data to the GDDS or to DTs. Considering the implementation of the GDDS is an overarching topic between two different EU funding programmes, DIGITAL and HORIZON, this article focused on reviewing the data and digital infrastructures relevant to the European Green Deal initiatives to address research gaps that exist between European Common Data Spaces (including the EOSC) and DTs, following the state of the art described in Section 2.

The rest of this article presents the Materials and Methods in Section 3 based on our systematic review of published articles, using the Web of Science database, associated with the interactions between data spaces and DTs. In addition, a secondary database, CORDIS, was explored to identify EU projects contributing to data spaces and/or DTs. To summarise the results in Section 4, the number of articles and projects dedicated to data spaces by sector was quantified, and this study focused on those that are relevant to the GDDS for further analysis. More specifically, the types of service components that serve as technical building blocks to implement a data space were identified in a summary table with their standards and technologies to determine the level of interoperability among GDDS initiatives and projects. Finally, key findings to address the current gaps and opportunities are highlighted and discussed in Section 5.

## 2. Background

### 2.1. Data Spaces

Following the European Strategy for Data, the Commission has been investing in a High-Impact Project on Common Data Spaces and federating cloud infrastructures in the period 2021–2027 [7] to fund infrastructures, data-sharing tools and services, architectures, and governance mechanisms based on the European federation of cloud infrastructures, namely Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Software-as-a-Service (SaaS), and Data-as-a-Service (DaaS) [32,33].

By building on the existing research community with the EOSC and adding other sectors, the European Commission has supported the establishment of the Common European Data Spaces, including data from public and private sectors as well as research institutions [34]. In this context, the stakeholders participating in sectoral data spaces range from public administrations (e.g., INSPIRE, national Spatial Data Infrastructure), industry (e.g., DIAS, Gaia-X), research and innovation (e.g., the EOSC), and citizen science [4,10,32,33,35].

#### 2.1.1. European Open Science Cloud

The European Open Science Cloud (EOSC) brings together institutional, national, and European stakeholders to develop a research data and services ecosystem in Europe [4]. Since 2018, the EOSC has been implemented under the Horizon 2020 (2018–2020) [4] and Horizon Europe (2021–2027) Programmes to provide seamless access and reliable reuse of research data to European researchers, innovators, companies, and citizens, through a trusted and open distributed data environment and related services [10]. Specifically, the

implementation of the EOSC Strategic Research and Innovation Agenda (SRIA) follows a three-stage approach [10]:

- Stage 1 (2021–2022): to deploy the core technical functions (EOSC Core) that enable the operations of the EOSC.
- Stage 2 (2023–2024): to expand the core data infrastructure for scientific research in key thematic areas as well as to connect the EOSC to the wider public sector (e.g., INSPIRE) and the private sector (e.g., Gaia-X).
- Stage 3 (2025–2027 and beyond): to enable European and national research infrastructures delivered from the Member States and Associated Countries to further expand the EOSC.

In recent years, different scientific communities have started developing thematic clouds within their domains of research and innovation, such as the ones developed by ESFRI (European Strategy Forum on Research Infrastructures). Such thematic cluster projects have been implemented since 2019 to be well connected to the EOSC in Stage 2, one of which is ENVRI-FAIR [36], which connects the Environmental Research Infrastructure community (ENVRI) to the EOSC ecosystem. For all these participating Research Infrastructures, the overarching goal is to build a set of FAIR (Findable, Accessible, Interoperable, and Reusable) [37] data and services that are most relevant to the Green Deal and Agriculture sectors.

More recently, in Stage 2, following the establishment of the Data Space Support Centre (DSSC), a collaboration between the DSSC and the EOSC Association (a legal entity since 2020) was initiated in early 2023 on a cross-sectoral level [38]. Starting with the co-organised introductory webinar, more joint events followed during the EOSC Symposium and the European Big Data Value Forum. At the strategic level, the EOSC Association participates in the DSSC Strategic Stakeholder Forum (SSF), in support of landscaping the Common European Data Spaces as well as in alignment with achieving the goals of EOSC SRIA [38].

### 2.1.2. Green Deal Data Space

The European Green Deal (EGD) is one of the top European Commission's priorities to tackle climate change and environmental degradation [39]. To overcome these challenges, the EGD's aim is that Europe becomes the first climate-neutral continent, reducing net greenhouse gas emissions by at least 55% by 2030, compared to the 1990 level, to achieve net zero emissions by 2050 [39]. Environmental monitoring is a key tool for knowing the level of achievement in many EGD targets.

In support of the Green Deal priority actions on climate change, circular economy, zero-pollution, biodiversity, deforestation, and compliance assurance, the European Commission announced its intention to assess the interaction between the INSPIRE Directive on environmental geospatial data and the directive on public access to environmental information, in the context of the GreenData4All initiative [7,40,41]. The aim is to modernise both directives in alignment with the current state of IT for sharing public, private, and citizen-generated data [10,40,42].

Under the EU's DIGITAL Programme, the CSA project GREAT [43] has aimed to establish the GDDS foundation built on both the European Green Deal and the EU's Strategy for Data. When GREAT ended in April 2024, five key pillars were reported in the project deliverables:

- Community of Practice (CoP): Open CoP of data providers, users, and intermediaries from diverse stakeholder communities participating in all phases from co-design to implementation, supported by use cases identified by the DSSC [44].
- Blueprint: The reference of the technical architecture setting the data and service technical interoperability framework and defining the common services enabling federated discovery, access, processing, and reuse of data [44].
- Priority dataset: The Minimum Viable GDDS, defining an expandable core set of high-value datasets for the first implementation phase of the data ecosystem federation [45].

- Governance and Business Models: An open and inclusive multi-stakeholder governance scheme defining federation business processes, roles, and policies and the trust framework [46].
- Roadmap: The high-level roadmap defining the future implementation (2025–2027) and capacity building steps [47].

In addition to the GREAT project, the European Commission identifies four HORIZON projects for Innovation and Action as key GDDS initiatives [8]: AD4GD, B3, FAIRiCUBE, and USAGE.

### 2.1.3. Technical Building Blocks for Data Spaces

As implementing data spaces requires different technical capabilities in the blueprint structure, technical building blocks are defined in three categories by the DSSC [32,48]:

- T1. Data interoperability enables the exchange of data, such as semantic data models, data formats, and interface APIs, including functionalities for provenance and tracking the processing of data sharing.
- T2. Data sovereignty and trust enable the identification of participants and assets in a data space, sovereignty over their shared data and the enforcement of policies agreed on regarding data access and usage control.
- T3. Data value creation enables data providers to register data offerings or services, publish their description to be discovered following the FAIR principles, and provide marketplace functionality.

The structure of nine technical building blocks [48] in Table 1 enables us to identify open standards and specifications in common for each of them.

**Table 1.** Three categories of technical building blocks Version 1.0. Source [48].

T1. Data Interoperability	T2. Data Sovereignty	T3. Data Value Creation
Data Model	Access and Usage	Metadata
Data Exchange	Identity	Publish and Discover
Provenance and Traceability	Trust Framework	Value-Added

## 2.2. Digital Twins

In ISO 23247-1 [49] a digital twin (DT) is defined as a “fit for purpose digital representation of an observable manufacturing element with a means to enable convergence between the element and its digital representation at an appropriate rate of synchronization”. The concept of DTs started in the 1990s; then, the models were initially applied to various industries, from manufacturing in the 2000s [50] to building [51–53], construction [54–56], and transportation [57,58]. Thus, DTs have been around for three decades, especially in industrial processes involving mathematical analysis, optimisation, or simulation models [59]. However, Big Data, Sensor Web, and AI systems have enabled the implementation of the DT paradigm in other sectors, such as healthcare and medicine, over the past few decades [30,31,60–62].

This paradigm based on a multi-disciplinary approach is now playing an important role in advancing the scientific state of the art [63], and in contributing to the European Green Deal strategy. The key objectives are overlapped across data space sectors, such as energy, mobility, manufacturing, and agriculture, towards energy efficiency of the built environment (i.e., carbon-neutral 2050) as well as the adaptation of our society and economy to climate change [63].

### 2.2.1. Digital Twin of the Earth

As a new DT of the Earth, Destination Earth (DestinE) is a key initiative of the European Commission to develop a highly accurate digital model of the Earth on a global scale, which will monitor, simulate, and predict the interaction between natural phenomena and human

activities [9,63]. It will contribute to achieving the objectives of the green and digital transitions as part of the European Commission's Green Deal and Digital Strategy [3,12,63].

Stated by the European Strategy for Data (2020) [7], the DestinE initiative aims to bring together European scientific and industrial excellence to develop a very high-precision digital model of the Earth. Since 2021, DestinE has been developing a digital modelling platform to visualise, monitor, and forecast natural and human activity on the planet in support of sustainable development and climate adaptation, thus supporting the European Green Deal [7,31]. DestinE features three core components [64]: the DestinE Service Platform (DESP) developed by ESA; DestinE Data Lake (DEDL) harmonised by EUMETSAT; and Digital Twin Engine (DTE), which is accessible to DTs on climate adaptation (Climate-DT) and extreme weather (Extremes-DT) implemented by ECMWF. In particular, DEDL provides seamless discovery, access, and Big Data processing services to a set of data spaces (Green Deal, Energy, Mobility, Finance, Industry, Health, and Agriculture) [64,65].

### 2.2.2. Digital Twin of the Ocean

With the thematic level of contribution to DestinE, the European Digital Twin Ocean (EDITO) has been invested in by the European Commission since 2021, under the EU mission Restore our Ocean and Water by 2030 [66]. EDITO is a digital platform that will provide access to vast amounts of data, models, artificial intelligence, and other tools, which will allow the replication of the properties and behaviours of marine systems, including ocean currents and waves, marine life and human activities, and their interactions, in and near the sea [67]. The core EDITO will be a public good, connecting the physical, biological, and socio-economic dimensions of the ocean, available to researchers, businesses, decision-makers, and citizens.

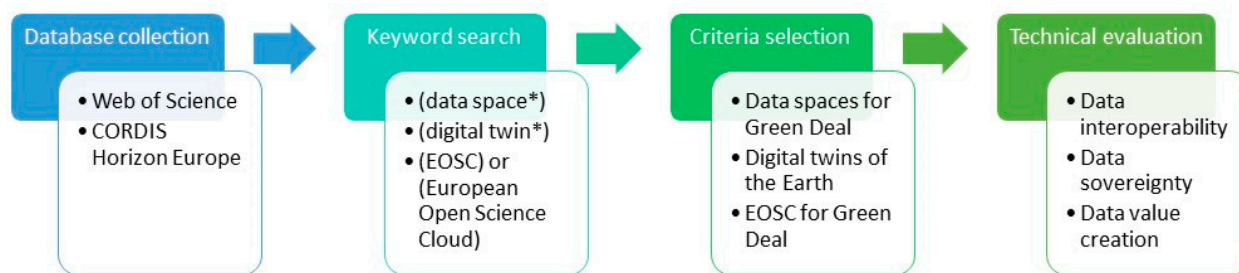
EDITO builds on existing core data infrastructures and ocean services, such as the Copernicus Marine Environmental Monitoring Service (CMEMS), Copernicus Data and Information Access Services (DIAS), and European Marine Observation and Data Network (EMODnet), in alignment with DestinE, to be interoperable [68]. In addition, related research projects under the HORIZON Programme contribute to the development of EDITO, namely EDITO-Infra, EDITO-Model Lab, ILIAD, IMMERSE, Blue-Cloud 2026, and AquaINFRA [68].

### 2.3. Research and Innovation (R&I) Relationship between EOSC, Data Spaces, and DTs

The focus of the above sections was on data spaces and DTs in a broader context across sectors. Since the ambition of creating Common European Data Spaces was relatively new at the time in 2020 and was not operational yet, a conventional literature review is not currently sufficient to analyse the relationship in research and innovation between DTs and data spaces, including the EOSC, while they are all evolving at the same time. Therefore, our main interest is to present the state of the art to the best of our knowledge and identify gaps specific to the R&I relationship between the EOSC, the GDDS, and DestinE in the context of the green and digital transitions.

## 3. Materials and Methods

A review of scientific articles without limiting the publication year was conducted. In addition, the European Commission's CORDIS database was used to support our review of the state of the art by obtaining complementary materials whose results have not yet been published in scientific articles. Mainly, we considered categorising the sectors of data spaces or DTs to be incorporated into the GDDS. Furthermore, we aimed to identify the service components implemented or planned in the searched articles and projects, in contribution to the technical building blocks in the GDDS. A simplified workflow diagram can be found in Figure 1.



**Figure 1.** Workflow of systematic literature review and selection. The asterisk wildcard character (\*) can include plurals.

### 3.1. Data Collection

The methodology of our systematic review combines assessing published articles on data spaces, including the EOSC, and on DTs using the Web of Science databases as the primary data source, complemented by HORIZON projects registered in the CORDIS database of EU research results, which were retrieved in January 2024. Motivated by the Open Science policy that is one of the new elements in the HORIZON Research and Innovation Programme, projects were collected as the secondary data source to support the state of the art on data spaces in progress.

- Web of Science: all databases.
- CORDIS: 10,045 HORIZON projects.

### 3.2. Search Strategy

Specifically, we first searched articles using the topic search (TS) in Web of Science with the following keywords:

- (data space\*), selected 6287 articles;
- (digital twin\*), selected 11,842 articles;
- (EOSC OR (European Open Science Cloud)), selected 133 articles;
- (data space\* AND digital twin\*), selected 18 articles that mention both keywords to reflect our main interest.

Furthermore, manually filtering by the title and abstract excluded irrelevant articles, such as the different definition of ‘data space’ (i.e., term used in geometry), which resulted in 16 articles. The criterion selected to filter those articles was the use of (data space\*) referring to the Common European Data Spaces, whether it was sector-specific or cross-sectoral.

Using the same topic search (TS) in Web of Science, we attempted to use other keyword combinations, including the EOSC:

- (data space\*) AND (EOSC OR (European Open Science Cloud)), selected 1 article;
- (digital twin\*) AND (EOSC OR (European Open Science Cloud)), selected 1 article;
- (data space\*) AND (digital twin\*) AND (EOSC OR (European Open Science Cloud)) selected 0 articles.

However, only a few articles were found with the above keyword combinations. The number of articles obtained using single or combined keywords is summarised in Table 2.

**Table 2.** Matrix of keywords combined and number of selected published articles.

Keyword	data space*	digital twin*	EOSC
data space*	6287	18	1
digital twin*	18	11,842	1
EOSC	1	1	133

Secondly, using the CORDIS database, we selected HORIZON projects based on the same keyword search by combining keywords (Table 3) and found the following additional information:

- (data space\*), selected 81 projects;
- (digital twin\*), selected 163 projects;
- (EOSC OR (European Open Science Cloud)), selected 49 projects;
- (data space\*) AND (digital twin\*), selected 18 projects;
- (data space\*) AND (EOSC OR (European Open Science Cloud)), selected 12 projects;
- (digital twin\*) AND (EOSC OR (European Open Science Cloud)), selected 4 projects;
- (data space\*) AND (digital twin\*) AND (EOSC OR (European Open Science Cloud)), selected 2 projects.

**Table 3.** Matrix of keywords combined and number of selected HORIZON projects.

Keyword	data space*	digital twin*	EOSC
data space*	81	18	12
digital twin*	18	163	4
EOSC	12	4	49

### 3.3. Data Extraction and Criteria

Key criteria were extracted in CSV format from the databases searched. These criteria include the title, authors, abstract, and publication year for Web of Science articles, as well as the project name, title, organisations, description, objectives, and start and end dates for HORIZON projects. Further details were analysed by gathering the full articles and project homepages to summarise and categorise sectors of data spaces, DTs, and the EOSC.

Based on the above-mentioned data extraction, our evaluation on the relationship between data spaces and DTs was focused on the following criteria:

- Data spaces contributing to the Green Deal (environmental data);
- DTs of the Earth (Earth observations);
- EOSC-related projects contributing to the Green Deal.

### 3.4. Technical Building Block Evaluation

Based on all the above information searched in the Web of Science and CORDIS databases, we evaluated whether the articles and projects found are considered relevant to the European Green Deal. More specifically, according to the three categories of technical building blocks introduced in Section 2.1.3, we aimed to identify service components (e.g., DaaS, SaaS, PaaS, IaaS) with open standards and specifications that could contribute to the creation of the GDDS.

## 4. Results

This section summarises the results of the keyword search using the Web of Science and CORDIS databases, highlighting the distribution by sector and the relationship between data spaces, DTs, and the EOSC.

### 4.1. Web of Science Articles

As summarised in Table 4, the earliest article was published in 2020 on the Industry Data Space (i.e., based on the existing Industry 4.0) whose sector has the highest number of 11 publications relating to DTs. Other sectors found in this topic search include Green Deal, Cultural Heritage, Mobility, and Energy. There was one article that analysed both the GDDS and DTs as well as their interaction [31].

**Table 4.** Summary of categorised articles in Web of Science with topic search ((data space\*) AND (digital twin\*)).

Sector	Publication Year	Title	Authors
Industry	2020	NDE Perception and Emerging Reality: NDE 4.0 Value Extraction	Vrana, J. [69]
	2021	An approach for Industrie 4.0-compliant and data-sovereign Digital Twins	Jacoby, M. et al. [70]
	2021	Smart Manufacturing Multi-Site Testbed with 5G and Beyond Connectivity	Harjula, I. et al. [71]
	2022	Data-driven hybrid petri-net based energy consumption behaviour modelling for digital twin of energy-efficient manufacturing system	Li, H.C. et al. [72]
	2022	Digital twin of spacecraft assembly cell and case study	Yang, W.Q. et al. [73]
	2023	On the Role of Digital Twins in Data Spaces	Volz, F. et al. [50]
	2023	Scalable Digital Twins for industry 4.0 digital services: a dataspaces approach	Moreno, T. et al. [74]
	2023	Interconnected digital twins and the future of digital manufacturing: Insights from a Delphi study	van Dyck, M. et al. [75]
	2023	Platform-based manufacturing	Tolio, TAM et al. [76]
	2023	A multi-level modelling and fidelity evaluation method of digital twins for creating smart production equipment in Industry 4.0	Zhang, C. et al. [77]
	2023	Information systems engineering with Digital Shadows: Concept and use cases in the Internet of Production	Liebenberg, M. and Jarke, M. [59]
Green Deal	2021	Digital Ecosystems for Developing Digital Twins of the Earth: The Destination Earth Case	Nativi, S. et al. [31]
Cultural Heritage	2022	Populating the Data Space for Cultural Heritage with Heritage Digital Twins	Niccolucci, F. et al. [78]
Mobility	2022	Enabling data spaces: Existing developments and challenges	Solmaz, G. et al. [79]
Energy	2022	Supporting Energy Digital Twins with Cloud Data Spaces: An Architectural Proposal	Rucco, C. et al. [60]
Cross-sector <sup>1</sup>	2022	Accessing spatial knowledge networks with maps	Jobst, M. and Gartner, G. [80]

<sup>1</sup> Applicable to multiple sectors.

While the topic search by “EOSC” returned 133 articles, the combination of EOSC with “data spaces” or “digital twins” returned only one article each, as presented in Tables 5 and 6.

**Table 5.** Summary of categorised articles in Web of Science with the topic search ((data space\*) AND (EOSC OR European Open Science Cloud)).

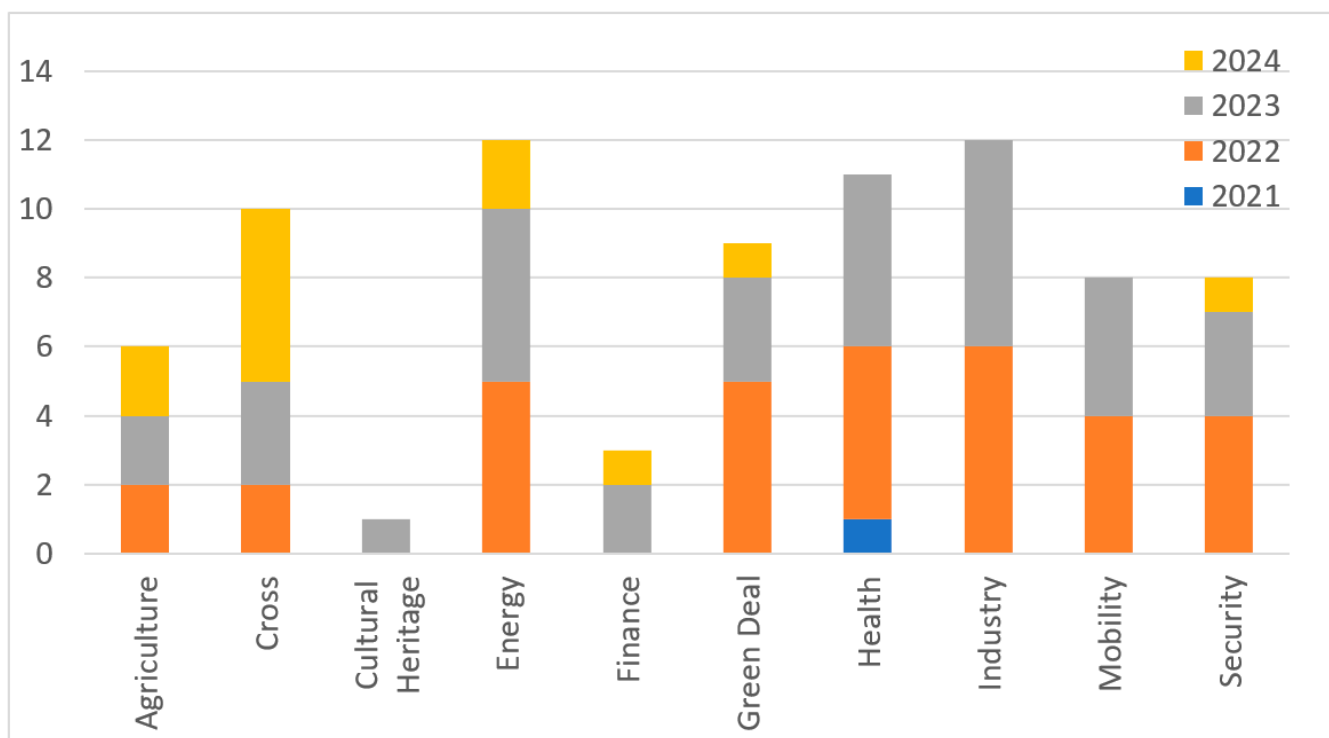
Sector	Publication Year	Title	Authors
Green Deal	2023	A Data Space for Climate Science in the European Open Science Cloud	Elia et al. [81]

**Table 6.** Summary of categorised articles in Web of Science with the topic search ((digital twin\*) AND (EOSC OR European Open Science Cloud)).

Sector	Publication Year	Title	Authors
Green Deal	2023	The role of the marine research infrastructures in the European marine observation landscape: present and future perspectives	Danobeitia et al. [82]

4.2. CORDIS—HORIZON Projects

As summarised in Figure 2, the earliest HORIZON project in any Common European Data Space started in the health sector in 2021, increasing to 11 on-going and expected projects in 2024, with the second highest number of projects among all data space sectors. While the industry sector highlighted in Web of Science ranks, first with 12 projects, the Energy sector also ranks first, with two new projects starting in 2024. In third place, nine projects have been awarded to the Green Deal sector, with a list of those projects presented in Table 7.



**Figure 2.** Distribution of HORIZON projects searched in CORDIS by keyword (data space\*) and summarised by sector and year.

**Table 7.** Summary of nine HORIZON projects contributing to GDDS.

Project Name	Start Year	Title
AD4GD	2022	All Data 4 Green Deal—An Integrated, FAIR Approach for the Common European Data Space
FAIRiCUBE	2022	F.A.I.R. information cube
interTwin	2022	An interdisciplinary Digital Twin Engine for science
USAGE	2022	Urban Data Spaces for Green dEal
Waterverse	2022	Water Data Management Ecosystem for Water Data Spaces
B3	2023	Biodiversity Building Blocks for policy
EuroGEOsec	2023	Establishing the EuroGEO Secretariat to support the EuroGEO initiative
Green.Dat.AI	2023	Energy-efficient AI-ready Data Spaces
MoRe4nature	2024	Empowering citizens in collaborative environmental compliance assurance via MOnitoring, REporting and action

#### 4.2.1. Connection between Data Spaces and DTs

Table 8 summarised the HORIZON projects identified by keyword search combining (data space\*) AND (digital twin\*) to explore the relationships between the projects and their application in specific sectors. Although there were six projects found in industry followed by four projects in energy, only two projects (interTwin and Green.Dat.AI) were mostly relevant to the Green Deal.

**Table 8.** Summary of 18 HORIZON projects searched by keywords (data space\*) AND (digital twin\*).

Project Name	Start Year	Title	Sector
Circular TwAIIn	2022	AI Platform for Integrated Sustainable and Circular Manufacturing	Industry
Zero-SWARM	2022	ZERO-ENABLING SMART NETWORKED CONTROL FRAMEWORK FOR AGILE CYBER PHYSICAL PRODUCTION SYSTEMS OF SYSTEMS	Industry
AI REDGIO 5.0	2023	Regions and (E)DIHs alliance for AI-at-the-Edge adoption by European Industry 5.0 Manufacturing SMEs	Industry
DaCapo	2023	Digital assets and tools for Circular value chains and manufacturing products	Industry
FLEX4RES	2023	DATA SPACES FOR FLEXIBLE PRODUCTION LINES AND SUPPLY CHAINS FOR RESILIENT MANUFACTURING	Industry
AUTO-TWIN	2022	Digital Twin generation, operations, and maintenance in circular value chains	Industry
interTwin	2022	An interdisciplinary Digital Twin Engine for science	Green Deal
Green.Dat.AI	2023	Energy-efficient AI-ready Data Spaces	Green Deal
ENERSHARE	2022	European common EneRgy dataSpace framework enabling data sHaring-driven Across- and beyond-eneRgy sERVICES	Energy
OMEGA-X	2022	Orchestrating an interoperable sovereign federated Multi-vector Energy data space built on open standards and ready for GAia-X	Energy
ENPOWER	2023	Energy Activated Citizens and Data-Driven Energy-Secure Communities for a Consumer-Centric Energy System	Energy
TwinEU	2024	Digital Twin for Europe	Energy
eBRAIN-Health	2022	eBRAIN-Health—Actionable Multilevel Health Data	Health
ReNEW	2022	Resilience-centric Smart, Green, Networked EU Inland Waterways	Mobility
BatteReverse	2023	A next-generation automated, connected, and standardised process for increased safety, efficiency, and sustainability of Li-ion BATTERY REVERSE logistics	Mobility
COBALT	2023	Certification for Cybersecurity in EU ICT using Decentralized Digital Twinning	Security

Among the total of 163 projects searched by the keyword (digital twin\*), in addition to those presented in Table 8, several projects were identified to potentially contribute their DTs of the Earth to data spaces in the context of the Green Deal. Those projects include DT-GEO, ASPECT, EDITO-Model Lab, and LandSeaLot.

#### 4.2.2. Connection between Data Spaces and EOSC

Among all Common European Data Spaces, the EOSC is different for not being a sectoral data space due to the inclusion of interdisciplinary research data, as the European Commission stated [9] that “the European strategy for data recognised the EOSC as the basis for a science, research and innovation data space to be articulated with the new sectoral data spaces foreseen by the Strategy”. Furthermore, the European Commission suggested that the EOSC should be recognised as the overarching transverse European Data Space for research and be implemented as orthogonal and supplementary to sectoral European Data Spaces [34]. The EOSC shall also be recognised as an accelerator of the digital transition, comprising FAIR digital objects.

Among the total of 49 projects searched by keyword (EOSC), 12 of them indicated an interaction with (data space\*) to some extent, as shown in Table 9. In addition to those

combined by both keywords, several projects were identified to potentially contribute their research data and services to data spaces in the context of the Green Deal. Those projects include Blue-Cloud2026, AquaINFRA, DT-GEO, ENVRI-Hub NEXT, FAIR-EASE, iImagine, and IRISCC.

**Table 9.** Summary of 12 HORIZON projects searched by keywords (data space\*) AND (EOSC).

Project Name	Start Year	Title	Sector
BY-COVID	2021	Beyond COVID	Health
eBRAIN-Health	2022	eBRAIN-Health—Actionable Multilevel Health Data	Health
EOSC4Cancer	2022	A European-wide foundation to accelerate Data-driven Cancer Research	Health
AD4GD	2022	All Data 4 Green Deal—An Integrated, FAIR Approach for the Common European Data Space	Green Deal
interTwin	2022	An interdisciplinary Digital Twin Engine for science	Green Deal
MoRe4nature	2024	Empowering citizens in collaborative environmental compliance assurance via MONitoring, REporting and action	Green Deal
TANGO	2022	Digital Technologies ActiNg as a Gatekeeper to information and data fLOws	Security
FAIR-IMPACT	2022	Expanding FAIR Solutions across EOSC	Cross
DATAMITE	2023	DATA Monetization, Interoperability, Trading & Exchange	Cross
EXA4MIND	2023	EXtreme Analytics for MINing Data spaces	Cross
EOSC Beyond	2024	EOSC Beyond: advancing innovation and collaboration for research	Cross
NOUS	2024	A catalyst for EuropeaN ClOud Services in the era of data spaces, high-performance and edge computing	Cross

#### 4.2.3. Connection between DTs and EOSC

What is still not evident is the relationship between DTs and the EOSC. There were only four projects selected by the keywords (digital twin\*) AND (EOSC), three of which were relevant to the Green Deal sector, as summarised in Table 10. It may be transitional for DTs to provide FAIR digital objects applicable from industry to research and innovation for improving monitoring and prediction [83]. Therefore, interoperability with DTs shall be the value added to EOSC resources federated by research infrastructures, and FAIR-by-design digital research outputs will become more prominent [84].

**Table 10.** Summary of four HORIZON projects searched by keywords (digital twin\*) AND (EOSC).

Project Name	Start Year	Title	Sector
eBRAIN-Health	2022	eBRAIN-Health—Actionable Multilevel Health Data	Health
DT-GEO	2022	A Digital Twin for GEOphysical extremes	Green Deal
interTwin	2022	An interdisciplinary Digital Twin Engine for science	Green Deal
Blue-Cloud 2026	2023	A federated European FAIR and Open Research Ecosystem for oceans, seas, coastal and inland waters	Green Deal

Overall, it should be noted that two projects, eBRAIN-Health and interTwin, contain three keywords in common, as listed in Tables 8–10, highlighting the interTwin categorised in the Green Deal sector.

#### 4.3. Technical Building Blocks for GDDS

By consolidating the initiatives and projects relevant to the GDDS presented in Tables 4–10, we visualised the relationships among them to identify the collaboration opportunities mapped in Figure 3. Firstly, the names represented in green boxes are relevant to the GDDS. Those in blue boxes are connected to DTs of the Earth, with some collaboration with the GDDS by GEOSS Portal, Green.Dat.AI, and interTwin. Those in pink boxes are EOSC-related stakeholders, some of which are collaborating with the GDDS

through ENES Portal, AD4GD, and interTwin. Lastly, the relationship between DTs of the Earth and the EOSC is highlighted in orange boxes, represented by Blue-Cloud 2026, DT-GEO, and interTwin.



**Figure 3.** Stakeholder mapping of collaboration opportunities among the projects and initiatives relevant to the GDDS, DTs of the Earth, and the EOSC.

We excluded new projects missing implementation details in their work plans, as well as initiatives, such as the European Ocean Observing System [82] (Table 6) and EuroGEOsec, which focus on the coordination of relevant stakeholders rather than the implementation of service components. Instead, we included active GDDS initiatives, represented in yellow boxes, supported by the European Commission, such as the Copernicus Data Space Ecosystem (CDSE) [85] and the Infrastructure for Spatial Information in Europe (INSPIRE) [86] mentioned in the above-reviewed articles and projects. Based on this selection, we further aimed to identify gaps and opportunities by category of technical building blocks that can be contributed by R&I stakeholders to the GDDS. More specifically, we evaluated the types of service components in development that are relevant to technical building blocks, as detailed in Table 11.

**Table 11.** Gap analysis of technical building blocks of selected initiatives relevant to GDDS.

Article EC Initiative Project (ID)	Year	Service Level	Service Name	Specification of Technical Building Blocks								
				T1. Interoperability			T2. Sovereignty			T3. Value Creation		
				Data Model	Data Exchange	Provenance Traceability	Access Usage	Identity	Trust Framework	Metadata	Publish Discover	Value-Added
Nativi, S. et al. [31,64,87]	2021	PaaS	DestinE Service Platform (DESP)			OpenAPI	OAuth, SAML	IAM (Keycloak) OpenID Connect	SIMPL			Marketplace
		DaaS	DestinE Data Lake (DEDL)				Harmonised Data Access (HDA) OpenAPI	OpenID Connect		STAC	STAC, HDA OpenAPI	Big Data Processing
		PaaS	GEOSS Platform	Domain Ontology Model	REST	ISO 19115-2 [88]	OpenSearch		CoreTrustSeal, Nestor Seal, ISO 16363 [89]	ISO 19115 [90]	GEO Discovery and Access Broker (DAB)	GEOSS Portal (ESA)
Elia et al. [81]	2023	PaaS	ENES Data Space Portal	CF Convention	NetCDF, REST		OAuth2, AAI (EGI)	AAI (EGI)		CMIP6	Earth System Grid Federation (ESGF) Catalogue, CMIP6	Marketplace (EOSC)
Copernicus [85]	2023	PaaS	Copernicus Data Space Ecosystem (CDSE)		OData, REST	OpenAPI	OpenSearch	OpenID Connect	S3 Credentials (AWS)	STAC	STAC, OpenSearch Catalogue	Sentinel Hub, openEO, JupyterLab
INSPIRE [86]	2022	PaaS	INSPIRE Geoportal (GeoNetwork)	INSPIRE Data Models	OGC (WFS, WCS, SOS, STA), REST		AAA (ARE3NA)	AAA (ARE3NA)	INSPIRE Re3gistry	ISO 19139 [91], (Geo)DCAT-AP	CSW ISO AP, GeoNetwork	INSPIRE Knowledge Base
AD4GD (101061001) [92]	2022	PaaS	AD4GD Data Space	Darwin Core, SAREF, Smart Data Models, CF, CCOS ECVs, GEO BON EBVs, RAINBOW	OGC Data Exchange Toolkit, JSON-LD, SPARQL, SensorThings API (STA), REST	OGC API Records, W3C PROV-O	IAM (Keycloak)	IAM (Keycloak)	IDS, EDC Connectors	ISO 19115 [90] (Geo)DCAT	GeoNetwork Catalogue	Green Deal Information Model
AquaINFRA (101094434) [93]	2023	PaaS	AquaINFRA Interactive Platform (AIP)	Water Ontology, ISO/TC 211 [94]	OGC APIs	OGC API Records	EOSC AAI	EOSC AAI		CKAN	OGC CWS, CKAN Catalogue	Marketplace (EOSC)
ASPECT (101081460) [95]	2023	SaaS DaaS	Seamless Climate Information System	CF Convention, WMO GRIB	NetCDF, GRIB		ESGF, MARS	ESGF		ISO, INSPIRE	ESGF, MARS	Climate Data Store, C3S
B3 (101059592) [96]	2023	SaaS	Occurrence Cube	Darwin Core, CF Convention	NetCDF, RDF, JSON-LD, OWL, REST		GBIF Registry, GEO BON Registry	GBIF Registry GEO BON Registry	CoreTrustSeal	Ecological Metadata Language (EML), DataCite	GBIF Catalogue, GEO BON EBV Catalogue	GBIF Portal, EBV Data Portal
Blue-Cloud 2026 (101094227) [97]	2023	PaaS	Blue-Cloud Open Science Platform	NERC	EUDAT	W3C PROV	AAI (EGI)	IAM (Keycloak)		ISO 19115 [90], ISO 19139 [91], DCAT	DAB, CKAN Catalogue	Marketplace (EOSC)
DT-GEO (101058129) [98]	2022	PaaS	DT-GEO Platform	Common European Research Information Format		COMPSS	FENIX AAI	FENIX AAI		FAIR EVA Tool	EPOS ICS-C Metadata Catalogue	Marketplace (EOSC)
EDITO-Infra (101101473) [99]	2022	PaaS	EDITO Platform				IAM (Keycloak), OAuth2	IAM (Keycloak), OpenID Connect	Traefik		EDITO Catalogue	Marketplace
EDITO-Infra (101101473) [99]	2022	DaaS	EDITO Data Lake	CF Convention, Darwin Core, WoRMS, EUNIS	OGC APIs, NetCDF					STAC	STAC, Resto	DestinE Data Lake

Table 11. Cont.

Article EC Initiative Project (ID)	Year	Service Level	Service Name	Specification of Technical Building Blocks									
				T1. Interoperability			T2. Sovereignty			T3. Value Creation			
				Data Model	Data Exchange	Provenance Traceability	Access Usage	Identity	Trust Framework	Metadata	Publish Discover	Value-Added	
EDITO-Model Lab (101093293) [100]	2023	SaaS	Virtual Ocean Model Lab (VOML)										CMEMS, EDITO Engine
ENVRI-Hub NEXT (101131141) [101]	2024	PaaS	ENVRI-Hub	WMO ECVs			AAI (EGI)	AAI (EGI)				ENVRI Catalogue	Marketplace (EOSC)
FAIR-EASE (101058785) [102]	2022	PaaS	Earth Analytical Lab (EAL)	NERC, INSPIRE, Global Change Master Directory, Darwin Core, WoRMS	OGC APIs, REST, SPARQL, NetCDF, OWL, RDF	W3C PROV-O	AAAI	AAAI			ISO 19115 [90], ISO 19139 [91], DCAT, EML	DAB	Marketplace (EOSC)
FAIRiCUBE (101059238) [103]	2022	PaaS	FAIRiCUBE HUB	INSPIRE	OGC APIs, REST, NetCDF	W3C PROV-PRIMER	IAM (Keycloak)	IAM (Keycloak) OpenID Connect	S3 Credentials (AWS)	STAC, ISO 19115 [90], DCAT, INSPIRE		STAC Catalogue	Marketplace
Green.Dat.AI (101070416) [104]	2023	PaaS	GREEN.DAT.AI Platform	IDS Vocabulary Hubs	OGC STA, RDBS-O		IAM (Keycloak)	IAM (Keycloak)	Trusted Execution Environments (TEEs)			IDS Metadata Broker (Sovity), EDC Connector	AI Services Toolbox for Data Spaces
ILIAD (101037643) [105]	2022 H2020	PaaS	ILIAD DTO Platform	Ocean Information Model	OGC APIs, REST, SDKs, Distributed Data Access Protocols	UNESCO Ocean Best Practices System (OBPS)	OAuth2	X509, identity4EO (DEIMOS)			(Geo) DCAT-IP	NEXTGEOSS DataHub Catalogue	Iliad Marketplace
iMagine (101058625) [106]	2022	PaaS	iMagine IT Platform	Darwin Core, WoRMS, FISHBase	NetCDF	Darwin Core Archive (DwC-A)	AAI (EGI)	AAI (EGI)	CoreTrustSeal		DwC-A	IMIS Catalogue	Marketplace (EOSC)
IMMERSE (821926) [107]	2018	SaaS	NEMO	CF Convention, Ocean Model	NetCDF					CECILL Software Licence [108]			Copernicus CMEMS
interTwin (101058386) [109]	2022	PaaS	Digital Twin Engine (DTE)	CF Convention	NetCDF, HDF5, GRIB, Open Neural Network Exchange (ONNX)	W3C PROV-DM	AAI (EGI)	AAI (EGI)	SIMPL		STAC, ISO 19115 [90], INSPIRE	STAC Catalogue	Marketplace EOSC
IRISCC (101131261) [110]	2024	IaaS					EOSC AAI (EGI)	EOSC AAI (EGI)				IRISCC Catalogue	Marketplace (EOSC)
LandSeaLot (101134575) [111]	2024	SaaS DaaS	LandSeaLot Integration Labs (ILs)	NERC	Ocean Data View (ODV) ASCII, NetCDF		SeaDataNet Common Data Index (CDI)				SeaDataNet Metadata Services	SeaDataNet CDI	LandSeaLot Portal, EMODnet, Copernicus, DTO
USAGE (101059950) [112]	2022	IaaS	USAGE Catalogue (GeoCat Live)	ISO 19131 [113], OASC MIM2	OGC Data Exchange Toolkit	W3C PROV-O					ISO 19115 [90], (Geo)DCAT	GeoDCAT Catalogue	Marketplace
Wataverse (101070262) [114]	2022	DaaS SaaS	Water Data Management Ecosystem (WDME)	Water Ontology, Smart Data Models	NGSI-LD Context Broker, JSON-LD	Blockchain	Identity Access Tool, OAuth2	Identity Access Tool	WDME Tools (FIWARE)	DCAT-AP, Dublin Core, DataCite		CKAN Catalogue	WDME Data Portal

## 5. Discussion

In this article, the potential key roles of research and innovation projects that interconnect the EOSC, the GDDS, and DTs of the Earth were explored. Searching the Web of Science and CORDIS databases, we found research projects with great potential, such as Blue-Cloud 2026, DT-GEO, and interTwin, to bridge research infrastructures and digital infrastructures in the Green Deal sector, as illustrated in Figure 3, at the strategic level. Nevertheless, manifesting a gap and opportunity for new topics in future HORIZON Programme calls to increase research-oriented data and services provided by the EOSC will enable them to be more interoperable with the DTs and consequently with industry-oriented data spaces. Through Open Science, research and innovation shall be shared and supported by public and private sectors, in coordination with the DIGITAL Programme, to accelerate the green and digital transitions.

Firstly, interoperability between all Common European Data Spaces, including the EOSC, is a necessary condition to better support relevant EU priorities, such as the Green Deal and the Digital Strategy. The results in Table 11 present a myriad of standards and specifications used by different GDDS initiatives, leading to the interoperability gap identified in this analysis. While the standards used are well documented, each initiative and project uses its own set of standards, preventing the final goal of creating a single data space. Secondly, DTs will fundamentally require interconnecting across the Common European Data Spaces to be effective. In practical terms, there are opportunities for main infrastructure providers of the EOSC to be the connecting nodes to federate not only other EOSC nodes but also such sectoral data spaces and DTs [115]. One of them is the European Grid Infrastructure (EGI) Foundation, which participates in key projects, such as Blue-Cloud 2026, interTwin, and GREAT. These providers can deploy interoperable horizontal services across sectors, such as the common Authentication and Authorisation Infrastructure (AAI) provided by the EGI (Table 11), which enables the integration of secured infrastructures and components, authenticating a wide range of stakeholders, including the public, private, and research sectors, as well as citizen communities [42,116]. Still, this may not be sufficient for connecting research objects provided by the EOSC to different sectoral data spaces that use domain-specific standards and different connector solutions. Such cross-sectoral data spaces are expected to be interconnected by the open Smart Middleware Platform (SIMPL) funded by the European Commission [117].

We emphasise that the EOSC is an evolving ecosystem articulated with multiple data and services that can be useful for several data spaces [48]. To accelerate the EOSC's evolution, the European Commission has recently launched the new EOSC EU Node [118], which will be a reference to federate other EOSC Nodes and extend research and innovation in public and private sectors and e-infrastructures across the EOSC ecosystem [119]. The EOSC Beyond project [120] will first test the selected pilot nodes, ranging from national (e.g., NFDI in Germany, e-Infra CZ in Czechia) to regional (e.g., NI4OS in South-Eastern Europe) and thematic (e.g., LifeWatch, METROFood-RI, Instruct-ERIC) levels, as well as expanding to ESFRI thematic clusters, research infrastructures, and virtual research environments. LifeWatch is featured as the first Environmental EOSC Node for validating the integration of the metadata catalogue into the EOSC. Within EOSC Beyond, the ENES Data Space will be further tested for integrating ENES climate change applications into EOSC Core services [73,120]. In addition, GDDS initiatives, such as ENVRI-Hub and the Copernicus Data Space Ecosystem, can play a key role in thematic EOSC Nodes.

With our focus on technical (also known as syntactic) and semantic interoperability at the operational level, we aimed to identify integration and harmonisation approaches among selected projects and initiatives relevant to the implementation of the GDDS, specifically by technical building blocks that require common (meta)data models, formats, standards, protocols, and agreements. Targeting software developers and service providers in both research infrastructures and digital infrastructures, the overall findings in Table 11 indicate that the FAIR principles [37] are better adopted by HORIZON projects [121] than the projects under the previous H2020 Programme Framework [122] due to the recently

released technical building blocks to support making data Findable (Metadata, Publish and Discover), Accessible (Access and Usage), Interoperable (Data Model and Exchange), and Reusable (Provenance and Traceability). Our evaluation demonstrates that most of the technical building blocks within T1 (Interoperability) and T3 (Value Creation) were implemented at the PaaS level. This is mainly because common standards to achieve interoperability are internationally used in data models (e.g., Climate and Forest—CF Conventions, Natural Environment Research Council—NERC Vocabulary Server, Darwin Core, Essential Biodiversity Variables—EBVs), data exchange (e.g., REST, OGC APIs, NetCDF, NGSI-LD, JSON-LD), and provenance (e.g., W3C PROV, ISO 19115-2). For creating value-added data, metadata formats and standards (e.g., ISO, DCAT, CKAN) are closely dependent on their hosting catalogues (e.g., GeoNetwork, STAC), marketplaces (e.g., EOSC, EDITO), and portals (e.g., GEOSS, CDSE, GBIF).

Analysing the T2 (Sovereignty) category, there are also several options to separate or combine access usage and identity building blocks using federated AAI, AAA (Authentication, Authorisation, and Accounting), and IAM (Identity and Access Management), such as EGI Check-in and Keycloak. However, trust frameworks are still not common yet, representing a gap to be filled at all service levels. There is a promising new Trust Framework derived from the industry-based data space arena, currently being developed by Gaia-X and iSHARE [123,124]. According to the iSHARE initiative [124], it defines the assurance levels of the participants on a framework and data space level. The DSSC considers that trust frameworks are in alignment with organisational building blocks that are closely interlinked with governance and legal implementations, beyond the technical ones. For example, the latest federated infrastructures by ENVRI for Research Infrastructures and the European Research Infrastructure Consortiums (ERICs) have already implemented almost all the technical building blocks [84,125], except for the trust framework, which will most likely require connectors included in SIMPL infrastructure services. The development of the federation approach adopted by the ENVRI-Hub NEXT project may become a thematic EOSC Node [119] that should also be included in the GDDS.

Even prior to the release of SIMPL middleware, expected to occur in late 2024, we identified a few projects, such as AD4GD, USAGE, Green.Dat.AI, and Waterverse, that use or implement industry-derived specifications recommended by the International Data Spaces Association (IDSA) and the DSSC [32,126]. Those specifications for technical building blocks include IDS Vocabulary Hubs, Smart Data Models, NGSI-LD Context Broker, IDS Metadata Broker, IDS Connectors, and the Eclipse Dataspace Component (EDC) Connector. The rest of the projects and initiatives may welcome public and open SIMPL services. We also identified this gap in the project timeline as a potential risk for those EU-funded projects that are waiting to decide on what interoperable services to use at data, infrastructure, and administrative levels until SIMPL becomes available. There is the possibility that SIMPL may not fulfil all the expectations of being an agnostic, scalable, or robust solution for all use cases. Each project might need to delay testing the SIMPL services and to be flexible for the adoption of complementary or alternative components by others, such as FIWARE [127] and EDCs [128] supported by the IDSA and the DSSC. Those projects that already use federated systems for specific building blocks will require scaling up or extending with connectors provided by SIMPL or the DSSC where possible.

## 6. Conclusions

Although our evaluation was not exhaustive among all data spaces, it listed selected projects and initiatives that could interconnect the EOSC, the GDDS, and DTs of the Earth, based on limited public resources, such as deliverables, publications, and conference presentations, which are currently made available on CORDIS results pages or their project websites. Further analysis of these projects may bring more references and insights to GDDS project participants and information about the synergies across projects, regardless of the sector. The key to success in co-creating the GDDS involves a combination of the following:

- A top-down approach with fundamental infrastructures composed of well-defined technical building blocks as the reference framework, such as the EOSC EU node, as well as technical guidelines (e.g., the DSSC) and accepted standard implementation (e.g., SIMPL and other intermediary services) to accelerate digital transformation within and across sectors to enhance the integration between platforms across domains.
- A bottom-up approach with flexibility and robustness of service components contributed by various technologies adopted by different initiatives to increase the interoperability as well as support the implementation of the GDDS with EU research projects in collaboration with the DT initiatives (e.g., DestinE).

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