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Aligning interoperability architectures for digital agri-food platforms

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ABSTRACT

Interoperability is a critical challenge in Agri-food digitalisation, aligning with European data strategies and fostering pan-European cooperation, innovation, cost reduction, and market competition. Within the last years, the European Commission funded several projects to address interoperability in digital agriculture. We compare the projects IoF2020, ATLAS, and DEMETER which address interoperability for Agri-food systems with varying architectures and approaches, supported by the OpenDEI project. Interoperability, defined as the ability of systems to exchange and use information, encompasses multiple dimensions, including legal, organisational, semantic, and technical aspects. The analysis in this comparison focuses on the semantic and technical interoperability aspects of each project, covering architectural approaches, contextualization, marketplace functionalities, and user management and security measures.

The examined projects highlight a variety of solutions, including service-oriented, data-centric, and process-oriented approaches, with the optimal choice between them remaining open, and an emphasis on the need for data consistency and plausibility. Advancements in standards and technologies, such as NGSI-LD, OGC, GAIA-X, and DSBA's implementation-driven plan, indicate a shift toward open interoperability in the broader ecosystem.

1. Introduction

Interoperability among different systems is an important challenge for the ongoing digitalisation of Agri-food and farms. In line with the European data strategy expressed in the Data Act,[1] Data Governance Act,[2] and recently proposed Interoperable Europe Act.[3] This plays a pivotal role in fostering pan-European cooperation, encouraging innovations, reducing costs, and enhancing market competition in support of the Common Agriculture Policy (CAP) and the European Green Deal strategy. An increasing number of systems with innovative functionalities are being offered by EU projects with the natural tendency of heterogenization, necessitating the ability to interoperate on both levels of data and services. The compared projects, funded by the European Horizon 2020 programme, each with a duration of more than 3 years, with more than 40+ partners, adopted approaches to address interoperability for Agri-food systems. The projects have evaluated more than 50 different use cases within domains such as arable crops, precision farming, fruit & vegetables, livestock, and supply chain. The proposed

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[1] European Commission (2022). Data Act: measures for a fair and innovative data economy. EU report. Brussels, Belgium.European Commission (2022). Regulation of the European Parliament and the of the council on harmonised rules on fair access to and use of data (Data Act). 2022/0047. EU report. Brussels, Belgium.

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0767.

[3] https://commission.europa.eu/publications/interoperable-europe-act-proposal-0_en.

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solutions were also evaluated respecting multiple stakeholders, including machinery and service providers, value adders and developers, as well as agriculture communities giving insights into exploitation potential and guiding future evolution. Three projects, IoF2020[4] (Internet of Food and Farm 2020) (Verdouw et al., 2017), ATLAS[5] (Agricultural Interoperability and Analysis System) (Rilling, et al., 2021), and DEMETER[6] (Building and Interoperable, Data-Driven, Innovative and Sustainable European Agri-food Sector) (Roussaki et al., 2022), show varying architectures, technologies, and approaches. These variations reflect the dependency of consortia composition and project-specific technical focus. This study addresses the challenge of interoperability in digitalising Agri-food, aligning with the European data strategy, and compares the three projects — across diverse agricultural domains, guided by the OpenDEI[7] framework for interoperability analysis (Kung et al., 2022).

The rest of the article provides a comparative analysis of the projects (section 2), following a consistent structure. Section 3 presents conclusions and recommendations for future work.

Further project descriptions are found in the appropriate references provided in the tables.

2. Comparison of approaches

The comparative analysis is adopted as a method to analyse the different project approaches for semantic interoperability, data models and ontologies.[8] We expect that the aspect of semantic interoperability will have significant future impact for Agri-food data sharing and thus can be considered as a key-aspect. The lens of comparison is constructed in such a way that each approach is weighted equally by having the same definition of semantic interoperability. Data models and ontologies are considered essential elements to design semantically interoperable Agri-food platforms that can facilitate different views. Therefore, these elements are selected as grounds for comparison.

2.1. *Semantic interoperability – data models and ontologies*

Semantic interoperability in the analysed projects is addressed from multiple angles and varies both in scope and expression. As ecosystem integration across the value chain creates multiple perspectives that can be considered, semantics have two main applications. The first one is the definition of the data models that helps to understand the real meaning of data expression and data models depicting relations between data. In an environment with heterogeneous data sources and models, data models enable data mesh-ups and aggregations. More widely, it is required to build scientific and operational inferencing enabling advanced analysis. The formal definition of the data can be expressed on multiple specificity levels; from generic (e.g., OWL (Web Ontology Language), RDF (Resource Description Framework), NGSI-LD (Next Generation Service Interfaces – Linked Data)), through activity-specific (e.g., SAREF (Smart Applications Reference Ontology)) to domain-specific (smart Agri-food). Semantic data can also be described in more human-readable terms in textual and graphical (UML (Unified Modeling Language), concept graphs) form.

The second area is on the verge of data semantics and technical interoperability through services discoverability, matching, mediation, and final binding harmonised among the ecosystems. IDS RAM (International Data Spaces – Reference Architecture Model) (Steinbuss et al., 2019) proposes a continuum of 3 levels: descriptive, declarative, specific/executables. We adopted three levels for our comparative analysis. Each level serves a distinct purpose in providing a comprehensive understanding of the ecosystem of each of the projects.

	IoF2020	ATLAS	DEMETER
General Approach	Explored multiple standards for descriptive and declarative modeling based on the Smart Data Models Agri.[a] It exploits the NGSI-LD for information cataloguing. Smart Data Models is practice-focused and lightweight and defines typical data 'entities' in an objective manner. The ecosystem is defined on a multilayer canvas with references to FIWARE[b] adapted to service catalogue based on the use cases and components (IoF2020 Compilation of Use Case Requirements, 2018); FIWARE (2020).	Semantic interoperability is a central concept of the ATLAS Interoperability Network through strict standardization. Service Templates describe these standards, they are use-case-driven functional definitions of services. The framework does not tackle the semantics of the data models, while template definitions define vendor- and technology-agnostic formal specifications of the APIs (Application Programming Interface), parameters, and data formats. The level of formalism depends on the instance.Service catalogue defines ecosystem roles and refers to preferred technical standards.[c]	Demeter's semantic support is based on the Agriculture Information Model (AIM), using OWL/RDF to collect domain and general vocabularies and define formal translations. It proposes modules (Saref4Agri based) – like Smart Data Models but focused on formality (European Interoperability Framework (EIF), 2023).Service definitions are based on the AIM model, whileService catalogue descriptions in the Demeter Enabler Hub define ecosystem roles and have without classification and mentioning some technical parameters.
Descriptive	Data frames and properties textual definition, text references to vocabularies e.g., GSMA (Global System for Mobile Communications), GeoJSON (Geographical JavaScript Object Notation) example,[d] DCAT-AP (Data Catalogue Vocabulary – Application Profiles). Based on: GS1 (Global Standards One), GSMA, reference model Argo (rmAgro), opplafy,[e] ADAPT (A Decentralized Application Programming Toolkit) definitions formal references to NGSI-LD context.	The model description is a significant part of the Service Template description. Considered vocabularies are described in the Service Template document.	AIM documentation is available as an open ontology[f] and project deliverable explaining considerations, decisions and graphically presenting model modules and references, including mapping to standards like FIWARE agri-food, SAREF4AGRI, Adapt, INSPIRE. FOODIE, AgroVoc, OWL, RDF, SKOS (Simple Knowledge Organisation Systems), NGSI-LD, SOSA (Sensor Open Systems Architecture), etc.
Declarative	Models use NGSI-LD context and URN-based (Uniform	Defined as bottom-up through references in	AIM is formal OWL/RDF definition, any

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[4] https://www.iof2020.eu/.
[5] https://www.atlas-h2020.eu/.
[6] https://h2020-demeter.eu/.
[7] https://www.opendei.eu/projects/agri-food-sector_new/.
[8] https://writingcenter.fas.harvard.edu/pages/how-write-comparative-analysis.

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	IoF2020	ATLAS	DEMETER
	Resource Name) referencing between instances. Domain classes formalised in JSON-LD context files.[g]the domain reference model, rmAgro,[h] was further elaborated on the sub-domains of animal and plant protection products (Urdu et al., 2022). The model is developed based on essential standards like ISO 11783, and thus expected to facilitate interoperable ways for modelling the agricultural domain.	Service Templates descriptions.	term expressed using AIM has class defined in known Generic ontologies (OWL, RDF. NGSI-LD). domain-specific (agriculture, Earth Observation (EO), when relevant.
Specific	The Open API (Swagger) YAML (Yet Another Markup Language) schemas, including examples in JSON-LD,are available. The catalogue contains harmonised internal metadata structures from the legal, business, and extent to impact. Components of the value chain can define functions e.g., particular data ingestion or analytics.	Recommended references from the Service Templates definition. No arbitrary references.Some provide examples of data such as application_info. info, nutrients gr, and unit recommendation. Service Templates are defined on the schemas and implementation levels with specific properties.	Demeter provides experimental schemes and SHACL (Shapes Constraint Language) shapes for validating saref4agri data. The Demeter ecosystem hub implements registration and access management services, including implemented roles (org, application, producer, consumer) end technical AAA models and endpoints (authentication and access endpoints).

[a]https://github.com/smart-data-models/dataModel.Agri-food/tree/master.
[b]https://www.fiware.org/.
[c]https://drive.google.com/file/d/1-o4-WHp8hW_CSCTbxOcWvo-ZBy601wRs/view.
[d]https://github.com/smart-data-models/dataModel.Agri-food/blob/master/AgriCrop/doc/spec.md.
[e]https://market.ioflab.opplafy.eu/#!/offering.
[f]http://agroportal.lirmm.fr/ontologies/DEMETER-AIM/?p=summary.
[g]https://raw.githubusercontent.com/smart-data-models/dataModel.Agri-food/master/context.jsonld.
[h]https://rm-agro.github.io/.
[i]https://www.iot-catalogue.com.

2.2. Architectural approach and overview

All three projects emphasise a federated ecosystem for interoperability, employing semantic services and models to varying degrees. All system architectures are facing challenges in handling heterogeneous data and advocating for decentralization of governance with quality assurance measures to build trust among stakeholders, reflecting diverse architectural and functional decompositions in the data value chain. The following table show the key-concepts of the architectural approach of each of the projects elaborated upon in the previous sections.

Project	Architectural approach
IoF2020	A layered architecture for IoT solutions, from physical to application, emphasizing interoperability, but notes a gap in addressing foreign third-party asset accessibility (Verdouw et al., 2017); (IoF2020, 2018); (SmartAgriHubs, 2019); (IoF2020 Report on Synergy Analysis, 2019). This led to the extension of the CoatRack component for authentication, authorization, and monetization, with a loose mapping between IoF2020 and DEMETER Reference Architectures (CoatRack Open Source component for access control, 2019).
ATLAS	The ATLAS Interoperability Network is a regulated peer-to-peer network encouraging trust among participants by employing limited central components that facilitate trusted connections, ensuring access only for software systems from identified participants through standardized APIs (Nagel, 2021; Day, 2020 ;Tummers et al., 2019 ; Pierpaoli et al., 2013; Pedersen et al., 2015).
DEMETER	The layered architecture of DEMETER aims to enhance interoperability and facilitate open collaboration in the agri-food chain, incorporating specified layers from Physical to Application, integrating public/open data, and addressing the discoverability of foreign third-party assets, with a loose mapping to the IoF2020 RA despite functional divergences (Bader, et al., 2020; Palma et al., 2022; ETSI. Context Information Management (CIM), 2019; ETSI. SmartM2M, 2019).

2.3. Contextualisation – including enabling support for digital twins

Contextual information provision, a vital aspect in digital agriculture, is supported across architectures of the three projects, with IoF2020 and DEMETER utilising established information models (e.g., AIM and NGSI-LD), while the ATLAS architecture integrates context management implicitly within standardised services, and all architectures facilitate the creation and use of digital twins.

Project	Contextualisation
IoF2020	The FIWARE Context Broker, utilised in IoF2020 and the Smart Cities domain, facilitated access to context-related information in several use cases by representing entities like land parcels, greenhouses, and farm equipment as Digital Twins, integrating data from diverse IoT devices with unique identification schemes like GLOBAL GAP (Good Agricultural Practices) or GS1 System-of-Systems vision for the Global Management of a Farm, 2022.
ATLAS	Contextualisation in ATLAS is achieved through compliance with the ATLAS Service Template, which formally specifies parameters, data formats, and operations for elemental agricultural processes, ensuring each data entity inherently carries the required context. ATLAS sets standards for services, including digital field twins and digital barn twins.
DEMETER	The DEMETER project does not propose a centralised context hub implementation. Instead, the AIM model offers a reference mechanism for localising data in space and time, linking data directly to uniquely identified entities through the NGSI-LD core model and SOSA.

All the projects manage large volumes of geospatial and spatiotemporal data, and the spatiotemporal context is important in many of the applied use cases and pilots.

2.4. Marketplaces of data and services

The IoF2020, ATLAS, and DEMETER projects deviate in motivations, stakeholder involvement, and technology focus for service and data in the diverse and heterogeneous domain of Agri-food. Yet, all three aim to provide reusable components for data and service marketplaces from distinct perspectives.

Project	The marketplace of data and services
IoF2020	The 33 IoF2020 use cases primarily focused on sharing data and services within controlled environments, operating under defined parties with restricted public access. Business models emphasised direct contractual relations over data-based revenue models, simplifying authentication, authorisation, payment, and system resilience. IoF2020 implemented a FIWARE-based marketplace and a specific marketplace

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Project	The marketplace of data and services
	for standards and code lists, fostering collaboration with AgGateway and GS1. Additionally, the IoF2020 use case and IoT Catalogue can be viewed as a marketplace with indirect data/services access (IoT catalogue, presenting IoF, 2022; AgriGateways Open Source components, 2022).
ATLAS	The ATLAS Interoperability Network is not a data-sharing platform, instead, it focuses on services that map to real-world agronomical needs, lacking a data marketplace.ATLAS Services are listed in the ATLAS Registry, facilitating trusted data exchange between participants. Additionally, a *Solution Catalogue is provided*, which enables end-users, for example, farmers, to discover services relevant to their agricultural needs.
DEMETER	DEMETER extended interoperability by incorporating agnostic architectural elements, facilitating a higher standardization of data exchange and infrastructure deployment across sectors. The integration of marketplaces can leverage these elements, paving the way for a federation of marketplaces and principles enabling data sources and services availability across platforms. Additionally, central building blocks allow the virtual merging of operational data sources for shared data spaces, offering new possibilities for data sharing and multi-purpose access.

2.5. *User management – identity, access, and trust*

The User Management pillar allows the identification, authentication, and authorisation of stakeholders operating in a data space for trusted interaction. It ensures that organisations, individuals, machines, and other entities are provided with acknowledged identities. Those identities can be authenticated and verified, including additional information provisioning, to be used by authorisation mechanisms to enable access and usage control. The main approaches followed by the three projects are *digital identities*, *authentication*, and *authorization*. The platforms provide these capabilities for organisations, individuals, and devices. This aligns with the ongoing trend of realising data spaces that are viewed as key to achieve sovereign, interoperable, and trustworthy data-sharing across businesses and societies – a key step to the Data Economy of the future. In relation to this, the Big Data Value Association (BDVA), FIWARE, Gaia-X and the International Data Spaces Association (IDSA) decided to join forces and formed the Data Spaces Business Alliance (DSBA) to drive the adoption of data spaces across Europe and beyond. The following table shows the key-aspects in user management for each of the projects.

Project	User Management
IoF2020	Discussions on IoT solutions altered to physical access instead of managing identities, with certain solutions relying on local proprietary solutions without requiring access to public networks. Approaches with login and password for local installations were preferred, including implementations of FIWARE, GS1, and MS Azure. IoF2020 developed the CoatRack open-source software for access control, logging of usage, and dashboard display of access that is also the baseline for monetisation. CoatRack offers user interfaces for service providers and users. Based on a lightweight gateway with API keys, it is possible to provide access to services in a multi-sided marketplace environment. This facilitates N-to-M relations for service provision, access control, and service monetisation, including monitoring and visualisation functionalities.
ATLAS	As ATLAS is not a platform but a network of participants providing software systems, which implement ATLAS-compliant services or clients connecting to ATLAS services. There is no central user management, instead each participant offering a software solution like an FMIS, is responsible for managing user accounts management on their systems. A "pairing" mechanism based on OAuth2 facilitates the establishment of trusted data channels between two systems on behalf of a user (Internet Engineering Task Force, 2012).
DEMETER	Demeter's authentication. authorisation, accounting, and-clearing system is built on the integrated components, including FIWARE Identity Provider for OAuth2 authentication, XACML (eXtensible Access Control Markup Language) PDP (Policy Decision Point) for access management, Capability Manager, and Policy Enforcement Point for authorization, and a Traceability Agent with a Blockchain Repository for logging all the access operations (FIWARE Keyrock GE, 2019).

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3. Conclusions and future plans

This work examined three European projects addressing interoperability in digital agriculture, focusing on technical and semantic interoperability, architectures, contextual information, marketplaces, and user management. Interoperability solutions for Agri-food data sharing include service-oriented, data-centric, and process-oriented approaches. Service-oriented systems facilitate accelerated market uptake and support data sharing on behalf of the data owner (typically referred to as "user account"). Data-centric systems, like GAIA-X, include dedicated data objects for improved data-sharing and complex solutions. The optimal choice between the two approaches remains still open. With both approaches, agricultural data can be made available on a large scale, necessitating data consistency, plausibility, and immutability.

The analysed three projects present diverse approaches to data models, semantics, and contextualisation. Where IoF2020 focuses on simplicity, DEMETER bet on the formal definition of the interoperability space, and ATLAS models agricultural processes with standardised services. Common tendencies include loosely coupled components integration, lightweight encodings, and standards exploitation based on market practices. Aligning these approaches raises questions.

Following the trend of growing data volumes and increasing heterogeneity caused by cross-domain initiatives, supporting machine readability will help to increase the scale and speed to undertake collaborative research.[9]

An open ecosystem fostering innovation and collaboration benefits from top domain solutions such as NGSI-LD and OGC (Open Geospatial Consortium) standards while remaining open to other technology stacks. Recent INSPIRE (Infrastructure for Spatial Information in the European Community) recommendations emphasize solution-agnostic interoperability and openness, promoting off-the-shelf applications that can leverage standards to stimulate value creation.[10]

Approaches presented in projects like 'AllData4GreenDeal' (AD4GD) and 'Iliad – Digital Twin of the Ocean' aim to exploit semantic interoperability for the European Green Deal, Data Spaces, and the Ocean Digital Twins markets (EU Commission, 2019; Berre, 2007). Aligned with initiatives such as GAIA-X, European- and International Data Spaces, and DestinE,[11] DEMETER AIM is promoted as an OGC standard, within projects like DIVINE,[12] contributing to open interoperability in the Agri-food chain. Recent efforts in standards and technologies, including INSPIRE (Minghini et al., 2020; Kotsev et al., 2021), Green Deal policies, and industry advancements, are facilitating new levels of open interoperability. Some examples are the DCAT profiles, advancements of 'Observation, Measurements and Samples' standard (previous ISO 19156:2011), GeoSPARQL (OGC/ISO) Spatial Data on the Web (W3C/OGC), JSON-LD WG (W3C) and ITU-T (International Telecommunication Union). Balancing open and proprietary software solutions is crucial for market competitiveness and innovation.

The achievements in this paper resonate with the broader ecosystem, such as the Data Spaces Business Alliance (DSBA), fostering convergence

[9] https://doi.org/10.5194/egusphere-egu22-11012.

[10] https://eur-lex.europa.eu/resource.html?uri=cellar:9d14b97c-029f-11ed-acce-01aa75ed71a1.0001.02/DOC_1&format=PDF.

[11] https://digital-strategy.ec.europa.eu/en/policies/destination-earth.

[12] https://cordis.europa.eu/project/id/101060884.

across sectors. DSBA's implementation-driven plan utilises existing technologies for creating data spaces, including NGSI-LD API and Smart Data Models to ensure data interoperability. For ensuring Data Sovereignty and Trust, anchor functions, including a decentralized Identity and Access Management (IAM) framework, based on OpenID Connect and ABAC (Attribute Based Access Control) is proposed. The Service Catalogue and Marketplace functions are based on TM Forum standards and ensure data value creation. This effort sets the stage for future activities in the smart Agri-food domain, contributing to the European industrial landscape.

The above-mentioned convergence effort and technical coherence pathway will pave the way to future activities in the smart Agri-food domain, representing a relevant market for the European industrial landscape.

CRediT authorship contribution statement

Daoud Urdu: Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. **Arne J. Berre:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Formal analysis, Conceptualization. **Harald Sundmaeker:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Formal analysis, Conceptualization. **Stefan Rilling:** Writing – review & editing, Writing – original draft, Resources, Investigation, Formal analysis, Conceptualization. **Ioanna Roussaki:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Formal analysis, Conceptualization. **Angelo Marguglio:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Kevin Doolin:** Writing – review & editing, Resources, Investigation, Formal analysis, Conceptualization. **Piotr Zaborowski:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Rob Atkinson:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Raul Palma:** Writing – review & editing, Validation, Resources, Conceptualization. **Marianna Faraldi:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Sjaak Wolfert:** Writing – review & 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

Data will be made available on request.

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