Integrating Agricultural Semantic Models with Data Spaces for Enhanced Interoperability

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***Abstract*—Digitalization is transforming agriculture by boosting productivity, sustainability, and efficiency. Yet, the potential of technologies like IoT, AI, Big Data analytics, and robotics is limited by interoperability challenges, including fragmented data sources and heterogeneous models. In this work, we explore how data spaces can enhance interoperability and secure data sharing in agriculture. Within the AgriDataValue (ADV) project, we leverage the Agricultural Information Model (AIM) and integrate it with the International Data Spaces (IDS) Information Model. Our approach adapts AIM in pilot activities and establishes mappings to IDS, aiming to develop a unified ADV data model for seamless cross-pilot data sharing. By promoting standardized data models and governance frameworks, data spaces foster collaboration, improve decision-making, and drive sustainable, data-driven innovation in the agri-food sector. We demonstrate, in the context of ADV, how data spaces are able to reimagine agricultural ecosystems in a manner that promotes sustainability, efficiency, and innovation.**

***Index Terms*—digital agriculture, smart farming, interoperability, data spaces, agricultural ecosystems, semantics**

I. Introduction

Digitalization is rapidly growing in agriculture, particularly in the agrifood chain, driven by the latest improvements in productivity, sustainability and operational efficiency [1]. Essentially, it requires the integration of a variety of digital technologies, including Internet-of-Things (IoT), big data analytics, Artificial Intelligence (AI), and robotics; its full potential is often restricted due to various crucial interoperability challenges. Among these, major challenges that farmers face are related to identifying appropriate data sources, adopting models that adequately capture essential information, and seamlessly sharing data and knowledge across heterogeneous hardware and software resources.

These challenges severely impede the full realization of data-driven insights. Interoperability, which allows different components within a smart agriculture ecosystem to work harmoniously [2], is vital and, without it, data remain in silos, negatively affecting effective decision-making due to the unavailability or inaccessibility of holistic insights [2], [3]. The extended heterogeneity of non-interoperable technologies in the agricultural domain greatly reduces both the efficiency and the potential of the adopted solutions [4], [5]. Hence, the lack of interoperability among different technologies leads to ”information islands”, impeding the creation of integrated services across different platforms [2], [4]. The challenge of interoperability in the agriculture sector can be effectively addressed by developing a common agricultural data model that integrates and standardizes diverse data sources and systems utilized throughout the industry [2]–[4]. Such a model not only establishes a shared conceptual framework but also fosters collaboration among different systems and technologies.

In this context, data spaces present a promising solution, offering a secure and trusted environment for data exchange and collaboration [6]. Through the implementation of common standards, governance models, and technical infrastructure, data spaces facilitate seamless data flow between stakeholders in the agricultural domain, driving innovation and efficiency. This, in turn, empowers farmers to extract greater value from data, optimize resource utilization, and implement optimal farming and farm management practices.

This work explores the development of interoperable agricultural ecosystems by integrating the Agricultural Information Model (AIM) [7] and the IDS Information Model (IDS InfoModel) [8], based on the Data Spaces Protocol (DSP) [9], within the context of the AgriDataValue (ADV) project [10]. In this study, we aim to develop a structured interoperability framework for agricultural ecosystems by (i) integrating semantic modeling through the Agricultural Information Model (AIM) and (ii) enabling sovereign and standardized data sharing via Data Spaces mechanisms. Our goal is to foster seamless, cross-domain, and secure agricultural data exchanges without dependence on specific platforms or technologies.

II. Interoperability in Agricultural Ecosystems

A. Interoperability in the agriculture sector

*1) **The Power of Interoperability in Agriculture**:* Interoperability in agriculture refers to the seamless collaboration between different systems, technologies, and data sources, ensuring smooth communication and integration. As digital tools become increasingly embedded in farming, interoperability is key to enhancing productivity, sustainability, and resilience [11], [12], facilitating efficient data exchange among stakeholders, i.e. farmers, agronomists, researchers, and technology providers, driving informed decision-making and innovation.

A major benefit of interoperability is the enhanced *operational efficiency*. The cohesive functionality of agricultural machinery, IoT devices and cloud platforms optimizes workflows, minimizes redundancies, and effectively utilizes the available resources. This interconnected ecosystem supports real-time data exchange, enabling farmers to streamline processes, reduce costs, and improve productivity. Beyond efficiency, interoperability cultivates *sustainable farming*. Precision agriculture allows farmers to monitor real-time soil health, weather, and crop performance. This data-driven approach helps minimize the reliance on fertilizers, pesticides, and water, reducing environmental impact while ensuring long-term agricultural viability. Additionally, interoperability fosters *collaboration and technological progress*. Standardized data-sharing platforms connect farmers with researchers, agribusinesses, and policymakers, promoting collective problem-solving. This collaborative environment accelerates advancements in pest control, soil health management, climate adaptation, and smart irrigation. By integrating cutting-edge technologies and fostering strategic partnerships, interoperability lays the foundation for a more adaptive, efficient, and resilient agricultural future.

*2) **FAIrness, Semantic Interoperability and the AIM**:* The FAIR principles are a set of guidelines designed to improve the *Findability*, *Accessibility*, *Interoperability*, and *Reusability of data*. Adopting FAIR principles enhances interoperability, ensuring that data can be effectively shared and reused across systems and domains [13], [14]. A key enabler of FAIR principles is incorporating semantics, which facilitates meaningful data exchange and integration [15].

In this context, *semantic interoperability* plays a pivotal role in establishing a common understanding among various stakeholders within the agricultural domain; semantic interoperability is defined as the ability to exchange (meta)data with meaningful understanding among different systems [4], [5], [14]. Leveraging standardized vocabularies and ontologies, semantic technologies enable seamless data interpretation across heterogeneous systems and expert communities.

One of the most effective strategies for achieving semantic interoperability is through an ontological approach, which provides a structured and machine-readable representation of domain knowledge. This approach not only ensures consistency in data interpretation but also enhances the automation of processing and decision support mechanisms. For example, [16], employs semantics to enable effective communication and data exchange among diverse IoT systems, discussing the implementation of lightweight semantic annotation models and the use of ontologies to describe agricultural data streams. Similarly, the AfarCloud project [17] features a middleware that leverages semantic models defined by the AfarCloud ontology[1] to abstract the heterogeneity of underlying hardware (e.g. sensors, vehicles), ensuring that the entirety of stored information follows a unified model, guaranteeing interoperability. Furthermore, [13] presents an ontology-driven framework for farm animal health management, focusing on the development of the Livestock Health Ontology (LHO)[2] to enhance data interoperability and decision-making in agriculture. The framework adheres to the FAIR principles, promoting data accessibility and privacy while addressing challenges in data acquisition and integration.

Building on this ontological and semantic approach, the Agricultural Information Model (AIM) [7], developed within the DEMETER project [18], integrates both software and hardware by defining common vocabularies, data formats, and protocols, thus facilitating seamless communication between farm equipment, software applications, and IoT devices in the agricultural sector. In particular, the AIM employs ontologies between agricultural concepts (e.g. soil types, weather conditions, crop growth stages), while the inherent adoption of the NGSI-LD meta-model for property graph representation ensures compatibility across various domains. The resulting unified model assists in knowledge representation, allowing machines and systems to understand and process agricultural data more effectively, further promoting the desired interoperability among diverse agricultural systems.

In the context of this work, we adopted the AIM to enable interoperable data sharing across 23 pilots in 9 countries, validating the proposed model through real-world, multi-country implementations and ensuring seamless communication between heterogeneous agricultural systems.

B. Data Spaces and Interoperability

*1) **Data Spaces Projects**:* Data spaces play a critical role in addressing interoperability challenges by forming a trusted environment for agricultural stakeholders [19]. As part of the Common European Data Spaces [20] initiative under the European Data Strategy [21], the Common European Agricultural Data Space (CEADS) aims to facilitate secure and standardized data sharing across the agrifood sector [22]. Its deployment will build upon AgriDataSpace [23], a project that has laid the groundwork by defining its governance, technical framework, and implementation strategies. Divine [24], CrackSense [25], ScaleAgData [26], and AgriDataValue [10] are ongoing projects contributing to the CEADS.

Other independent initiatives for building data spaces in the agricultural sector, include the Digital Innovation Hub for Agriculture and Food Production Data Space (DADS) [27] initiative in Slovenia, which fosters a non-formal network of agrifood stakeholders, AgDataHub [28] in France, DJustConnect [29] in Flanders, Agrifood Data Space Finland (AFDSF) [30], and the METRIQA platform [31], which hosts Italy's agrifood data space. These initiatives highlight both the growing importance of data spaces in agriculture and the significant interoperability challenges that arise when integrating diverse actors and technologies within these ecosystems.

[1] https://git.code.tecnalia.com/afarcloud_public/ontology

[2] https://agroportal.lirmm.fr/ontologies/LHO

*2) **Data Spaces as an Interoperability Framework**:* Data spaces, as decentralized infrastructures, enable trusted, federated, and semantically interoperable data exchange between participants while maintaining data sovereignty [6], [32]. The International Data Spaces Reference Architecture Model (IDS-RAM) [33] provides a structured approach to achieving interoperability at multiple levels, including technical, semantic, organizational, and legal interoperability, as stated in the New European Interoperability Framework [34].

Within this framework, via the connectivity enabled by Data Connectors [35], semantic interoperability is achieved using common information models such as the IDS InfoModel and the adoption of domain-specific models, such as the AIM. These models establish a shared vocabulary that allows data providers and consumers to interpret data consistently, ensuring that agricultural data can be meaningfully exchanged and processed across different platforms. On this ground, data spaces create an environment where agricultural stakeholders can exchange data seamlessly while maintaining full control over their interpretation and usage.

For data ecosystems to function effectively, interoperability must occur both within a single data space (*intra-data space interoperability*) and between different data spaces (*inter-data space interoperability*) [36]. The latter is particularly critical when considering cross-domain interactions, as industries frequently rely on data from external sectors. Agriculture, by nature, interacts with multiple domains such as mobility, logistics, finance, energy, and others. For instance, farm irrigation optimization requires real-time climate data, integrating information from meteorological data sources; agricultural supply chains depend on logistics and retail data spaces, ensuring transparency and traceability of food products. Thus, inter-data space interoperability inherently includes cross-domain interoperability, as data space instances from different sectors must interoperate to reflect real-world dependencies. Agri-data spaces should be designed with this inter-connectivity in mind, allowing agricultural stakeholders to benefit from cross-sector insights.

*3) **Sovereign Data Sharing and the Dataspace Protocol**:* Interoperability enables seamless data exchange but requires a standardized protocol to maintain data sovereignty, security, and compliance [37]. Whether in networking, communication, or data exchange, a clear protocol ensures compatibility, security, and trust. Similarly, in data spaces, the *Dataspace Protocol (DSP)* [9] serves this role by providing a standardized, yet flexible mechanism for data sharing across federated environments. It defines a) *rules for data access, usage, and control*, ensuring that data providers retain sovereignty over their assets, b) *interoperability mechanisms* to align different data space implementations while respecting domain-specific requirements, and c) *security and compliance frameworks* that provide the basis for trust in cross-domain data exchanges. Building on this foundation, DSP is a mechanism that forms the basis of semantic interoperability by dictating how data should be shared between parties at a high level, providing a structured yet adaptable framework. This allows organizations to implement their custom requirements, such as usage policies, governance models, and security measures, while ensuring compatibility with the broader data space ecosystem.

In this work, we embraced data space technologies, i.e. the IDS InfoModel and DSP, to enhance interoperability — initially among project pilots, to be followed by external stakeholders. This approach contributes to the development of larger data ecosystems, while supporting the CEADS.

III. The AgriDataValue approach: Integration of AIM and IDS Information Model

AgriDataValue project adopts a dual-layered model by integrating the AIM for sector-specific communication while leveraging the IDS InfoModel for a domain-agnostic semantic interoperability mechanism. This combination ensures that agricultural stakeholders can exchange data efficiently within the sector while remaining interoperable with other industries, platforms, and data ecosystems. To support this approach, AgriDataValue has developed the *ADV Data Model*, an extension of the AIM that incorporates a domain-agnostic layer based on the IDS InfoModel.

The AIM structures agricultural data according to industry standards, ensuring that farmers, agribusinesses, and research institutions can communicate seamlessly using specialized ontologies and vocabularies. It enables precise, context-aware data sharing within the agricultural sector, ensuring compatibility with farm management systems, IoT platforms, and precision farming applications. Building on this sectorial alignment, IDS InfoModel acts as a universal data exchange mechanism, a lingua franca, that allows agricultural data to be shared among other domains such as climate science, logistics, finance, and manufacturing. IDS InfoModel provides a structured and interoperable data exchange framework, ensuring that data can be understood, accessed, and processed consistently, regardless of the domain. This critical distinction enables cross-sector innovation, automation, and scalability, as agricultural data must frequently interact with external industries for tasks such as climate-informed decision-making, supply chain optimization, and sustainability monitoring. This approach aligns agricultural data ecosystems with data space architectures, fostering effortless, structured, and sovereign data exchange across sectors.

To effectively integrate the AIM and IDS InfoModel, the AgriDataValue project follows a *five-step methodology* (Fig. 1) that ensures structured and reliable mapping of concepts between these models:

*1) **Understanding the Models**:* The first step involves a detailed analysis of both the AIM and IDS InfoModel, identifying their core elements, structures, and semantic relationships. This includes reviewing classes, properties, and relationships within each model to ensure their proper alignment.

*2) **Identifying Common Elements**:* After understanding the models, common concepts and relationships are identified. This involves detecting overlapping definitions, attributes, and shared entities that can be linked to create a proper mapping.

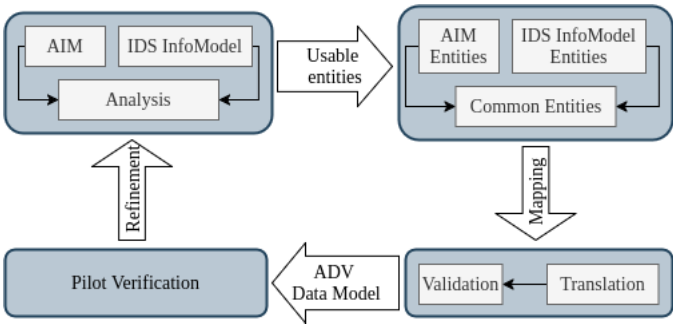

Fig. 1. Overview of the AgriDataValue interoperability approach, combining the Agricultural Information Model with the IDS Information Model to enable secure and seamless agricultural data exchange.

*3) **Mapping Elements**:* A systematic mapping is conducted to establish clear relationships between AIM's and IDS InfoModel's classes. This mapping allows for agricultural data, following domain-specific structures, to be transformed into a format understood by other sectors via the IDS InfoModel.

*4) **Implementing the Integration**:* Once the mappings are available in machine-readable format (JSON-LD), the ADV Data Model is constructed by extending AIM with a domain-agnostic layer derived from the IDS InfoModel. Validation and translation mechanisms complete the pre-pilot technical verification, ensuring that the mapped data models function correctly and that semantic interoperability between these models is effectively achieved before full-scale deployment.

*5) **Validation and Refinement via Pilots**:* The final step involves the validation of the model using real-world data from AgriDataValue's pilots. This ensures that data mappings are accurate, transformations are seamless, and interoperability goals are met. Feedback from stakeholders and domain experts is used to iteratively refine and improve the model.

TABLE I
SAMPLE MAPPING BETWEEN AIM AND IDS INFOMODEL

AIM Class	**IDS InfoModel Class**	**Description**
AgriParcel, AgriMachinery	Resource	Resources that contribute to farm operations.
AgriPest Instruments	Alert	Notifications about pest outbreaks affecting crops.
Crop, CropType	Product	Specific types of crops grown in agriculture.
Agricultural Contract	Contract	Agreements between agricultural stakeholders.
Sensor	DataAsset	Captures and transmits environmental and field data
Regulatory Framework	Policy	Compliance standards for agricultural practices.

Table I illustrates an example of structured mapping between the AIM and the IDS InfoModel, highlighting how agricultural data can be translated into a domain-agnostic format for interoperability. This mapping ensures that agricultural data can be seamlessly exchanged, not only within the sector but also with other industries. The integration follows a structured methodology, aligning AIM classes representing agricultural concepts with corresponding IDS InfoModel classes, providing a standardized framework for cross-domain data exchange. This table directly ties into the five-step approach adopted in AgriDataValue. Firstly, the process begins by analyzing both models and identifying common elements between AIM and IDS InfoModel. The systematic mapping of elements ensures that sector-specific agricultural data is structured in a way that external systems can interpret. The integration phase ensures that the mappings are implemented in a machine-readable format, utilizing translation and validation mechanisms before their verification in real-world pilots. The integration will result in the *ADV Data model* supporting diverse agricultural ecosystems, in alignment with the data spaces concept.

IV. AGRIDATAVALUE IN ACTION

In the AgriDataValue project, pilot diversity and multi-modal collection of measurements, ranging from IoT sensors' data to satellite and drone imagery, brings their common modelling to the proscenium, as a crucial element of an approach that envisages the integration of heterogeneous data sources into a versatile platform to achieve interoperability. Pilot sites utilize a variety of smart farming solutions for the collection of in-situ measurements from their parcels and stables. The operational and representational heterogeneity of these solutions makes the adoption of a domain-specific data model crucial for achieving homogeneity and harmonization within a common platform.

TABLE II
CORE ADOPTED AIM ENTITIES

Origin	**Adopted entities**
INSPIRE	ActivityComplex
FOODIE	CropType
SAREF	Sensor, Measurement
SAREF4AGRI	Building, Crop, AnimalGroup
Smart Agrifood	AgriParcel, Animal

On this ground, the domain-specific representation launched with the adoption of native AIM entities, and entities of diverse origins, including the Infrastructure for Spatial Information in Europe (INSPIRE) [38], the Smart Applications Reference Ontology (SAREF) [39], [40], and others. The adopted entities are summarized in Table II. The *ActivityComplex* is the top-level entity and describes an agricultural holding and/or farm, which *contains* plots, i.e. parcels, and/or buildings, i.e. stables. The parcel, described by its land utilization, soil texture and irrigation system type, might *contain* multiple crops. A crop includes, among others, information about the crop species, sowing and harvesting dates. On the other branch of the modelling, i.e. the one pertaining to animals, a stable might be the *location of* multiple animal groups with multiple animal *members*. Both parcel and stable entities *have devices* that *make* measurements. For reference, a sample AIM representation is depicted in Fig. 2. These core entities serve as the backbone of the common representation, and are subject to enrichment with supplementary information, depending on each pilot's data availability.

Having adopted entities essential for the representation of fundamental agricultural information, a methodology for

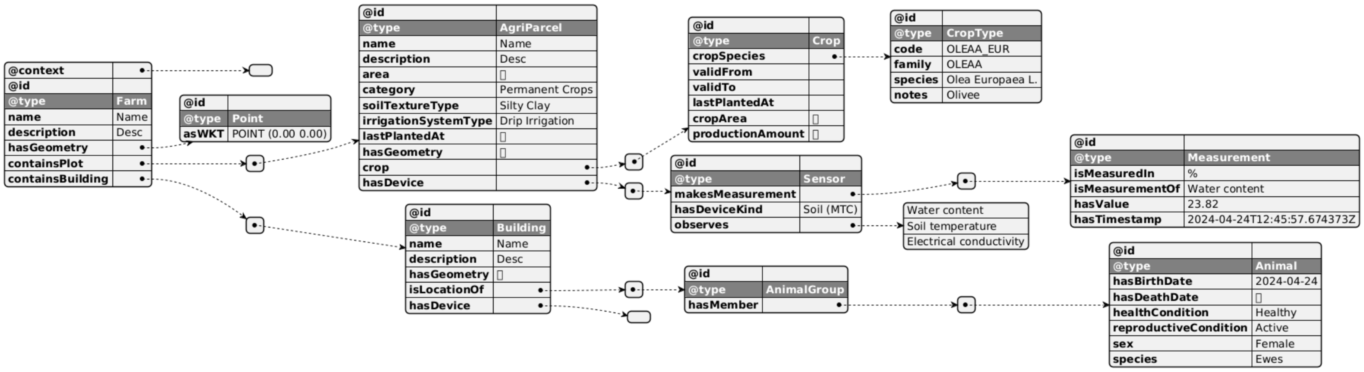

Fig. 2. Structure of agricultural entities adopting the Agricultural Information Model

translation has been developed to enable the transition from an external, third-party representation to the adopted common data model. In the ADV platform, which serves as the backbone of the system, eight (8) smart farming solutions have been integrated, as shown in Table III, covering the data collection needs across all pilots. After data acquisition, the entities and fields from the third-party platforms' internal representations are mapped to the adopted ones, interpolating with virtual entities when required, to enforce the required homogeneous and consistent information structure, ensuring that the collected agricultural data can be treated in a unified manner.

TABLE III
INTEGRATED SMART FARMING PLATFORMS

Provider	Platform
Synelixis Solutions S.A.	SynField[3]
Pessl Instruments	Field Climate by Metos[4]
Farm21	Farm21[5]
Green Project	Green Project API[6]
IFarming SRL	IFarming API[7]
MathWorks, Inc.	ThingSpeak[8]
ADCON Telemetry GmbH	ADCON LiveData[9]
Prointegra	Meteobot[10]

The procedures outlined for translating the collected agricultural information, adopting the ADV data model, accomplish part of the envisioned interoperability among a variety of smart farming solutions utilized in ADV's pilots. Nevertheless, the project's vision extends beyond the mere integration of these solutions into a single platform, aspiring to create an interoperable data space for agricultural information – hence the adoption of the IDS InfoModel.

Currently, agricultural information, captured in the AIM format, is included as an artifact within the IDS representation, which simply records the data exchange (e.g. contract, policy). This is due to the fact that during the initial part of the ADV project, emphasis was given to the homogenization of data originating from diverse smart farming platforms utilized in ADV's pilots, and the exchange of data among these pilots. Since data homogenization and exchange have been accomplished, the next focus is on achieving inter-sector interoperability for ADV's agricultural data space, via the adoption of the methodology described in Section III.

[3]https://app.synfield.gr/en/api/docs/
[4]https://api.fieldclimate.com/v2/docs/
[5]https://documenter.getpostman.com/view/10942265/U16ooPBk
[6]https://coreiot.green-projects.gr/docs/
[7]http://api.ifarming.info/dataprovisioning/api/
[8]https://www.mathworks.com/help/thingspeak/readdata.html
[9]https://www.otthydromet.com/en/about/our-brands/adcon
[10]https://meteobot.com/

V. CONCLUSION AND FUTURE WORK

In this work, a framework for the creation of interoperable agricultural ecosystems was presented. Beginning with a review of agriculture-focused interoperability and data spaces, we proceeded to the definition of the AgriDataValue approach, which serves as a paradigm for the seamless integration and homogenization of a variety of heterogeneous platforms. The combination of AIM, as a powerful data model for domain-specific data representation, alongside the IDS InfoModel, as an interoperability and data sharing enabler, forms a definite solution for the collection and exchange of agricultural information, while bridging the gap between the agricultural sector and seemingly external and/or unrelated industries.

To further validate and refine the proposed interoperability framework, realistic synthetic data-sharing scenarios will be developed and tested. These scenarios will simulate data exchanges between agricultural data spaces, as well as other domains such as mobility, logistics, and energy. This approach will allow for a comprehensive evaluation of semantic interoperability mechanisms under diverse conditions, ensuring that cross-domain data exchange is seamless, meaningful, and scalable. Future work will also focus on implementing and testing these scenarios using synthetic datasets, generated to mimic real-world agricultural and cross-domain data flows. This will include simulating use cases such as supply chain optimization through logistics data spaces, smart irrigation decisions based on AI services [41], and farm-to-market traceability leveraging mobility data spaces [42], [43]. Through pilot studies and controlled experiments, these scenarios will help identify potential challenges, refine mapping methodologies, and ensure the robustness of the ADV Data Model in enabling secure and sovereign data sharing across sectors.

The results and outcomes of this work, including the ADV Data Model, semantic mappings, and interoperability methodologies, will be made available as open-source resources, ensuring that stakeholders across different domains can reuse, adapt, and build on these solutions to enhance data interoperability and integration with their own ecosystems.

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