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Design and implementation of a data space application architecture for sovereign engineering collaboration

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Abstract

Collaborative product development across organizations is frequently challenged by heterogeneous IT landscapes, organization-bounded Product Lifecycle Management (PLM) systems, and insufficient trust in data exchange. These issues are especially critical in early design phases, where secure and seamless exchange of sensitive engineering data is essential. This paper presents a data space architecture designed to address these challenges. Building on these conceptual foundations, a prototype of a federated co-design application has been implemented, leveraging emerging data space technologies to enable secure and interoperable collaboration. This application follows Gaia-X principles and combines several key components: the Eclipse Dataspace Connector for secure and policy-based data exchange, the Open Digital Rights Language for machine-readable usage rules designed for contractual embedding, and the Asset Administration Shell for standardized asset representation. The architecture enables traceable workflows, granular access control, and semantic interoperability between distributed PLM systems, without centralizing data. By ensuring both technical interoperability and legal compliance, the platform shows how data spaces can support scalable, trusted, and sovereign co-design across organizations, and contributes a transferable architecture pattern that links co-design requirements to concrete data-space mechanisms. The prototype was evaluated by industry experts, providing valuable insights for future developments in this domain and clarifying how data-space concepts can be operationalized in early life-cycle co-design settings.

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Keywords: Data Space; Federated Collaboration; Data Sovereignty; PLM Integration

1. Introduction

Modern product development increasingly spans organizational boundaries, involving complex supplier networks and distributed engineering teams [1]. Many products are now co-designed by multiple companies to meet rising complexity and specialized market demands, with Original Equipment Manufacturers (OEMs) often relying on suppliers for the majority of components and value creation [2]. Such collaboration can accelerate innovation but also raises major challenges for information sharing and trust [3]. Early design phases are particularly critical, since companies need to exchange preliminary CAD models, requirements, and other intellectual property without jeopardizing competitive advantage [4]. From a Life Cycle Engineering (LCE) perspective, early design choices determine manufacturability, serviceability, and end-of-life options, making secure and traceable data exchange across partners essential. Federated

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data spaces provide a policy-driven approach to enable such exchanges while preserving data sovereignty [5].

This paper presents a requirements-driven, federated co-design architecture based on data-space principles [5]. It enables secure, interoperable, and policy-compliant sharing of engineering data across heterogeneous Product Lifecycle Management (PLM) environments. Key contributions include (1) an architecture that combines the Eclipse Dataspace Connector (EDC) for secure decentralized data transfer, the Open Digital Rights Language (ODRL) for machine-enforceable usage contracts, and the Asset Administration Shell (AAS) for standardized asset descriptions [6, 7, 8]; (2) a prototype implementation demonstrating cross-organizational CAD data exchange and collaboration between two institutions (one leveraging a PLM system and one using file-based storage) without centralizing data; and (3) a qualitative expert evaluation of functionality and trust features.

The remainder of the paper is structured as follows: Section 2 reviews related work and introduces the project context. Section 3 outlines the architecture, Section 4 describes the prototype, Section 5 presents evaluation results, and Section 6 concludes with implications for sovereign engineering collaboration.

2. Related work and project context

Heterogeneous IT landscapes and organization-bounded PLM systems limit seamless cross-company data exchange [9]. Cloud-based PLM collaboration solutions [10–12] improve accessibility but do not fully address interoperability, flexible onboarding, or data sovereignty concerns. Trust barriers persist because companies fear loss of control over sensitive design data, and the absence of usage-control standards reinforces these concerns [13].

In response, the concept of data spaces has emerged as a promising solution for sovereign data collaboration [14]. A data space is a federated data-sharing environment in which independent entities can share data under agreed policies without a central repository [15]. The International Data Spaces (IDS) architecture defines a reference model for decentralized exchange. It includes standardized connectors and governance models to enforce usage agreements [16]. Building on this foundation, initiatives like Gaia-X advance a federated European data infrastructure. The goal is to ensure interoperability and digital sovereignty in industry data sharing. These frameworks promote common standards (e.g., secure connectors, semantic metadata models) and machine-readable usage policies to enable trusted collaboration between organizations [17]. These emerging technologies make new platforms feasible. Engineering partners can share selected design data with fine-grained access control, trace data transactions, and automatically enforce licensing or confidentiality restrictions. This is particularly relevant in collaborative design use cases, where partners require timely and synchronized exchange of design files and models without compromising each party's autonomy [18].

The Austrian Manufacturing Innovation Data Space (AMIDS) provides the project context for this work. AMIDS implements a federated data space for the manufacturing sector, addressing challenges of interoperability, sovereignty, and collaboration. Within this project, requirements for cross-organizational co-design are defined and documented [19], and a co-design approach integrating data-space environments into project management is introduced [20]. These efforts form the methodological foundation for the present work.

From a scientific perspective, existing work on data spaces and PLM either remains at the conceptual reference-model level [14–17] or focuses on vendor-specific platforms [10–12] without addressing sovereignty-preserving co-design. Prior AMIDS work identified requirements for cross-organizational co-design [19,20] but did not show how to map them to concrete data-space mechanisms. This paper closes this gap by deriving a reusable architecture pattern linking co-design requirements to governance, interoperability, and usage-control mechanisms (EDC, ODRL, AAS), extending data-space research into early-stage life-cycle engineering.

3. Data space architecture for co-design

The proposed federated co-design architecture enables secure, policy-compliant, and interoperable collaboration across organizations. Following a layered principle, it separates user interaction, middleware, and data space services, ensuring modularity and adaptability to heterogeneous IT environments.

Fig. 1 illustrates the federated setup and main interaction flows. For clarity, only the infrastructure of Company 2 is shown, while redundant details for other companies are omitted. Earlier AMIDS developments, such as the Convenience Dataspace Connector (CDC) [21], which bridges the application with the data space, are directly embedded into the architecture. Building on these foundations, the application introduces co-design-specific functionalities. As illustrated in Fig. 1, each participant only needs to provide a storage or server instance, while additional services are offered through the AMIDS infrastructure. This low entry barrier also enables SMEs to participate in the collaboration process.

At the application layer, the Co-Design Application (CoDeApp) provides user-oriented features such as asset upload, metadata enrichment, policy definition, and PLM integration. Requests to the data space are routed through the CDC, which abstracts technical complexity. On the data space layer, the EDC manages contract negotiation, secure transfer, and policy-aware access control at transfer time, ensuring compliance with the decentralized governance model. Each shared asset is described through a submodel of the AAS and linked to a policy in ODRL. Together, these mechanisms enable traceable, sovereign exchange without central storage.

3.1. Core components and interactions

The architecture contains the following core components:

CoDeApp: A web interface for sharing design files, adding metadata, configuring policies, and linking PLM tools via APIs or adapters. Furthermore, workflow functions supporting cross-organizational co-design are implemented in the app.

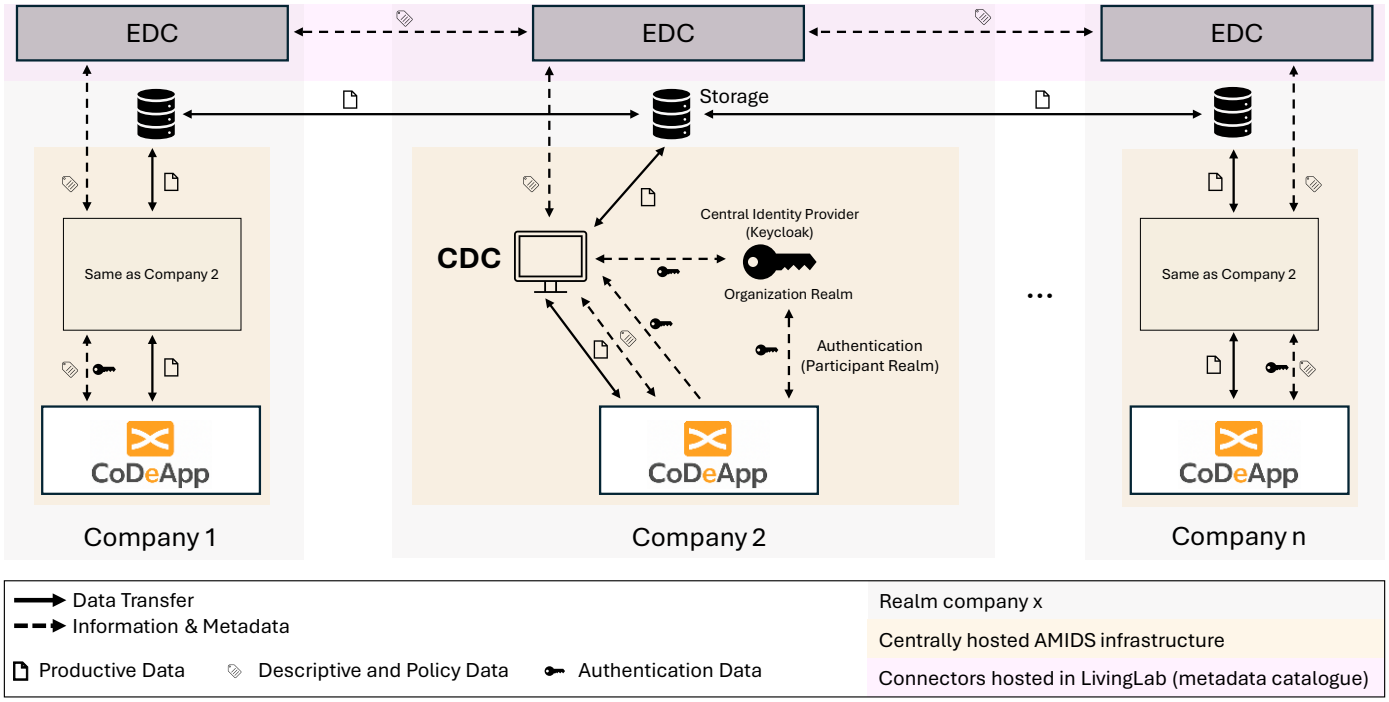

Fig. 1. Federated setup of the CoDeApp within the data space architecture, showing participating organizations, connectors, and central services, as well as the main interaction flows.

Convenience Dataspace Connector (CDC): The CDC is a middleware component between the CoDeApp and the EDC, developed in AMIDS to lower integration effort [21]. It handles authentication via Keycloak, provisions isolated organizational storage (e.g., S3 buckets [22]) and translates application calls into EDC-compliant protocol messages. Each participant receives a tenant instance of the CDC, which routes metadata and policy information to the EDC while keeping files in local storage. The CDC does not evaluate policies itself; enforcement occurs in the EDC. By abstracting these technical tasks, the CDC reduces complexity for new data space applications.

Eclipse Dataspace Connector (EDC): A connector for decentralized data exchange, policy-aware access control and negotiation at transfer time, and peer-to-peer transfer [6]; hosted in the T-Systems LivingLab [23].

Open Digital Rights Language (ODRL): Machine-readable usage rules attached as policies to each asset [7].

Asset Administration Shell (AAS): Each shared asset is described using the AAS. For CAD data, the submodel "Provision of 3D Models" is used, which captures metadata such as file type, version, and lifecycle status. For example, an uploaded file may be represented with the attributes {type: STEP, version: v1.2, lifecycle: in-work} [24]. This standardized structure enables asset discovery, versioning, and consistent policy binding. While the prototype focused on a minimal metadata set, the submodel can be extended with richer information (e.g., geometry details, confidentiality tags), ensuring scalability for more complex scenarios.

A typical workflow unfolds as follows: A user publishes a CAD file; metadata are structured as a submodel of the AAS and linked to an ODRL policy. The CDC forwards the offering to the EDC, which registers it in the catalog, while the file remains in the organization's designated storage (e.g., an Amazon S3 bucket). Consumers discover offers via metadata search, review policies, request access, and, upon successful policy evaluation and contract negotiation, receive a secure peer-to-peer data transfer.

3.2. Policy-based data exchange and legal safeguards

Trust and compliance in decentralized collaboration are supported by policy-based control mechanisms. Each data offering is accompanied by ODRL policies that specify conditions of use. These policies are evaluated by the EDC during contract negotiation and govern access decisions at the point of transfer. In addition, contractual agreements can be attached to the exchange, but their enforcement lies outside the EDC's technical scope and requires organizational or legal mechanisms. The architecture distinguishes several policy types:

- Membership policies: Define which organizations may join the data space.
- Catalog access policies: Regulate who can browse or search for available assets.
- Contract policies: Specify obligations and constraints for acquiring data.
- Usage policies: Restrict permissible actions after access (e.g., no redistribution, time-limited use).

By combining legal semantics (ODRL) with technical enforcement (EDC), the platform enables agreements to be machine-interpretable at negotiation and transfer time and auditable through transaction logs. Legal enforceability, however, requires contractual embedding beyond the technical scope of the EDC.

3.3. Handling tool heterogeneity and integration

Engineering collaboration typically involves diverse PLM and design tools. To avoid imposing a uniform system, the integration is handled directly in the co-design application. External tools connect via REST APIs or middleware adapters, enabling metadata extraction and automated updates.

The semantic abstraction is achieved by representing every shared asset as a shell in the AAS standard. This uniform representation allows heterogeneous tools to contribute assets that remain searchable and interoperable within the catalog. While the application handles tool-specific logic, the CDC and EDC remain agnostic of underlying systems, focusing solely on identity, routing, and secure exchange. This separation of concerns simplifies onboarding and ensures flexibility for future tool landscapes.

3.4. Onboarding and identity management

Onboarding a new organization involves deploying a dedicated CDC tenant and linking it with the central Keycloak identity service. Keycloak provides user authentication and role-based authorization, while the CDC binds these identities to the organization's storage and connector instance. Organizations are registered through a self-description process that specifies organizational metadata and agreement to common data space rules. Trust is therefore based on explicit organizational enrollment rather than ad hoc access. All user actions (e.g., publishing, requesting, or consuming assets) are authenticated and logged, ensuring accountability across participants.

4. Prototype implementation

Building on the architecture described in Chapter 3, a functional prototype of the federated co-design application was developed and tested in AMIDS. The prototype demonstrated the potential for cross-organizational collaboration between Graz University of Technology (TU Graz) and TU Wien and validated technical feasibility under realistic conditions. Although both partners were academic institutions, the collaboration replicated typical industrial co-design workflows using heterogeneous IT environments, data sovereignty requirements, and role distributions comparable to those found between manufacturing companies.

In this showcase, TU Graz connected its PLM environment via Teamcenter Share, while TU Wien participated without a PLM system, relying on local file storage. Both institutions accessed the data space through the Co-Design Application, which provided functions for asset upload, metadata enrichment, and policy definition. Secure and policy-compliant data transfer was realized through the CDC–EDC stack, ensuring that each transaction followed the technical and legal safeguards described in the architecture.

The prototype focused on three aspects: (1) user interaction through a dedicated web interface, (2) policy management through an ODRL generator and interpreter, and (3) metadata handling through the submodel "Provision of 3D Models" of the AAS [24].

4.1. Functionalities and technical implementation

To provide comprehensive functionality within a single environment, the CoDeApp integrates all the features necessary for data sharing, supporting both data providers and consumers. This includes the creation and interpretation of usage policies. The latter is particularly relevant for recipients, as ODRL policies are often complex and not trivial to interpret. A core functionality of the CoDeApp is the data upload section, which enables the publication of data offers. For this purpose, users are required to provide specific metadata to populate the corresponding submodel of the AAS. Complementing this functionality, a marketplace component was implemented to present all published offers of the corresponding connector.

Technically, CoDeApp is a web application with a React/TypeScript frontend and a Node.js backend. Data is transferred directly via the EDC without central storage. The app interacts with the EDC via the CDC. The prototype is hosted within the AMIDS infrastructure and is publicly accessible at https://co-design.amids.at.

4.2. Data flow and workflow realization

A typical workflow depicted in Fig. 2 proceeds as follows:

Onboarding: As a prerequisite, the two organizations are onboarded into AMIDS, authenticate via organizational self-descriptions, and accept common rules of the data space.

Policy generation: The user defines usage conditions (e.g., "read-only," "no redistribution," "time-limited access") with the integrated ODRL policy generator.

Publication: An engineer from TU Graz selects a CAD file via the Teamcenter Share Connector. Metadata (filename, version, file type) is extracted and structured as an AAS submodel. The CoDeApp sends references, metadata, and policy information to the CDC, which authenticates the user via Keycloak and routes the request to the EDC.

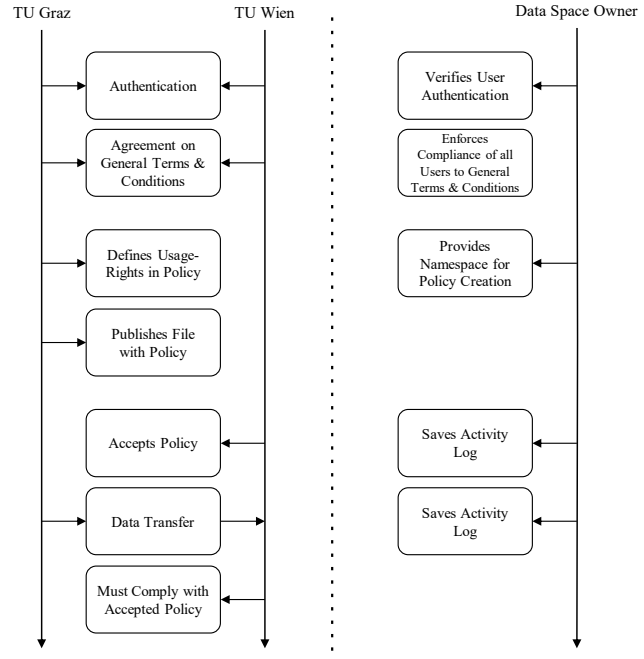

Fig. 2. Federated co-design workflow realized in the AMIDS prototype.

Discovery and request: An engineer from TU Wien accesses the catalog through the app, locates the asset, and requests access. This triggers a contract negotiation process in the EDC.

Policy evaluation and transfer: The EDC evaluates the attached ODRL policies. If conditions are satisfied, a contract is established, and the asset is securely transferred peer-to-peer between the connectors.

Consumption and interpretation: TU Wien receives the file, along with its associated policies and metadata. The ODRL interpreter in the application ensures that obligations (e.g., time-limited usage) are visible and actionable.

This workflow demonstrates that sensitive engineering data can be shared across organizational boundaries without central storage while retaining semantic structure and legal safeguards.

4.3. Policy generator and interpreter

A key feature of the prototype is the policy management interface, which enables users to create and interpret ODRL-based usage rules without requiring legal or technical expertise.

Policy generator: Implemented as a web-based form, the generator guides users through selecting conditions such as access duration, redistribution rights, or allowed purposes. Each choice maps to predefined ODRL patterns, ensuring semantic consistency. The resulting policies export in JSON-LD can be attached to the corresponding data offering.

Policy interpreter: On the consumer side, the interpreter translates ODRL statements into a human-readable summary, making obligations and restrictions transparent to engineers. For example, a "time-limited use" rule displays as a clear expiration date, while a "no redistribution" clause appears as a sharing restriction.

This combination of generator and interpreter shows how abstract legal concepts operationalize within engineering workflows, lowering the barrier for adoption and ensuring data space participants can both define and understand usage rules.

4.4. Limitations of the prototype

While the prototype demonstrates cross-organizational data exchange, it involves several simplifications. The integration is limited to connecting TU Graz via Teamcenter Share and TU Wien via local file storage; direct PLM-to-PLM synchronization is not implemented. The demonstrator focuses on isolated asset transfers. It excludes end-to-end workflows, such as automated propagation of design changes or process orchestration. Policy creation is restricted to basic usage conditions supported by the implemented ODRL interpreter, leaving complex contractual clauses unaddressed. Finally, scalability aspects, such as onboarding multiple organizations or handling large data volumes, are not evaluated, as the goal was to validate technical feasibility in a controlled testbed.

5. Evaluation and results

To assess the applicability and perceived value of the application, an exploratory qualitative evaluation with industrial experts was conducted. Because the system is still under development, a hybrid approach was used: (1) a running prototype demonstrated implemented functions such as CAD upload, metadata handling, and ODRL-based policy creation; and (2) a process diagram illustrated the envisioned end-to-end workflow, including not-yet-implemented elements like cross-company workflow automation and advanced PLM integration.

The evaluation sessions were carried out as semi-structured expert walkthroughs and lasted 45 to 60 minutes. Each session consisted of three phases:

- Current practice discussion: Experts reflected on existing workflows for CAD data sharing and collaboration.
- Prototype and process walkthrough: Core functionalities were demonstrated live in the prototype, while the broader workflow was explained using diagrams.
- Feedback and discussion: Experts provided qualitative feedback on usefulness, barriers, and adoption conditions.

In total, five experts from four different organizations participated in the evaluation. The participants represented the automotive and industrial manufacturing sectors, including large OEMs and SMEs, as well as an independent university representing academia. All participants had substantial experience in cross-organizational product development and CAD/PLM data exchange.

5.1. Preliminary findings

Perceived benefits: All participants considered the process meaningful and expected it to provide added value for organizations already collaborating with external partners and exchanging confidential data. Key advantages mentioned include (a) standardized and simplified CAD exchange process, (b) access to the latest files via version control, (c) improved traceability and transparency, and (d) simplified legal agreements through integrated policy management.

Challenges and barriers: Technically, participants did not anticipate major obstacles, as SMEs typically have sufficient IT expertise and server infrastructure. However, ease of deployment and use still needs validation in practice. Cost-benefit considerations were cited as decisive: adoption depends on how many partners use the platform and at what cost. End-user engagement is equally critical. While the platform provides up-to-date files, its effectiveness depends on continuous data maintenance by employees, requiring clear incentives and usability. Legal aspects remain unresolved, particularly in larger organizations with dedicated legal departments. Further investigation is needed to determine whether ODRL-based contracts would be accepted.

Suggested improvements: Participants suggested (1) a notification system for new file versions, (2) stronger integration with established tools (e.g., PLM systems, MS Teams), and (3) a request function for file access. These can be grouped into usability enhancements and integration features.

5.2. Limitations of the evaluation

The evaluation was limited to four organizations, restricting generalizability. As the CoDeApp is still under development, participants did not test it independently. Insights therefore capture perceived usefulness and adoption conditions rather than hands-on usability or efficiency gains. Future evaluations should involve larger groups and allow autonomous use of the app to better reveal challenges and improvement opportunities.

6. Conclusion and outlook

This paper introduced a requirements-driven data space architecture for cross-organizational co-design. The solution integrates the EDC for secure decentralized exchange, ODRL for machine-enforceable policies, and the AAS for semantic interoperability. A prototype validated technical feasibility between heterogeneous PLM environments, and expert feedback provided initial evidence of relevance and acceptance.

Scientifically, the work advances the state of the art by proposing a reusable architecture pattern that links co-design requirements to specific data-space mechanisms (EDC, ODRL, AAS), structuring usage control for engineering data spaces into four policy layers (membership, catalog, contract, usage), and empirically illustrating how these mechanisms influence trust and collaboration in realistic CAD/PLM settings.

From an LCE perspective, the approach strengthens continuity across the product life cycle by enabling traceability, sovereignty-preserving usage control, and trusted data exchange without central storage. This supports innovation ecosystems where secure collaboration is essential for sustainable, cost-efficient, and circular product development.

Limitations remain: Validation occurred in a confined testbed with limited participant diversity, focusing primarily on technical feasibility rather than large-scale adoption. Legal aspects of usage policies were addressed only conceptually. Furthermore, integration with commercial PLM systems was demonstrated only in simplified scenarios.

Future work will address these gaps by testing scalability under realistic workloads, advancing standardization of ODRL namespaces and policy templates, broadening PLM integration, and conducting legal validation of machine-readable policies to ensure contractual binding.

Advancing these areas will allow data space applications such as the CoDeApp to evolve into reliable infrastructures for trusted, scalable, life-cycle-aware engineering collaboration.

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