# Deliverable D31.2
# IDSA-compliant meta-data broker and discovery services in federated data space

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# 1. Executive Summary

The increasing digitalisation of the railway sector requires mechanisms that allow data and digital resources to be discovered and shared across organisational boundaries while preserving data sovereignty, security and interoperability. Within FP1-MOTIONAL, WP31 addresses these requirements through the development of a Federated Rail Data Space and its supporting technical components.

The objective of this deliverable is to define and demonstrate an interoperable approach for metadata publication, catalogue federation and resource discovery within the Federated Rail Data Space. The work follows a requirement-driven methodology, combining railway use-case analysis, architectural assessment, evaluation of relevant standards and technologies, and validation within the T-Systems Living Lab sandbox – while giving particular attention to the principles of data sovereignty, decentralisation, interoperability and integration with the connector infrastructure.

The analysis resulted in an architecture in which metadata brokering is implemented as a federated catalogue capability based on Eclipse Dataspace Components (EDC), rather than as a centralised metadata repository [1, 2]. Participating organisations publish metadata about their resources through their connector infrastructure. Catalogue information can subsequently be discovered by authorised consumers. This approach uses machine-readable metadata representations and established vocabularies, including JSON-LD, DCAT and ODRL, to support interoperable descriptions of resources, distributions and usage policies. The Federated Catalogue capability further supports catalogue aggregation through crawling and local caching, thereby reducing the need for repeated direct catalogue queries while retaining the federated character of the data space.

The resulting metadata discovery capability provides an enabling layer for the other components of WP31. In particular, it supports the App Store specified in D31.3 by providing the catalogue information, required to discover available assets and initiate subsequent contract negotiation and data transfer processes. D31.2 therefore forms an architectural link between resource providers, connector-based data exchange and user-facing applications such as the App Store.

The implementation and validation activities demonstrate the technical feasibility of the approach within the MOTIONAL Living Lab environment. The demonstrator shows that metadata can be published through EDC-based connector infrastructure, discovered through catalogue interactions and subsequently used as input to contract negotiation and data transfer workflows. The implementation therefore provides a suitable foundation for further development of federated resource discovery in the railway domain.

The main limitation is that the demonstrated implementation represents a project-specific sandbox environment and does not yet constitute a production-scale deployment of a European-wide Rail Data Space. In particular, the maturity of governance, participant onboarding, semantic harmonisation, large-scale catalogue federation and operational security requires further investigation.

Nevertheless, the results demonstrate that a federated catalogue approach is technically suitable for the metadata discovery requirements identified in MOTIONAL and provides a scalable basis for future integration with additional railway use cases and European data space initiatives.

## 2. Abbreviations and acronyms

| Abbreviation / Acronym | Description |
|---|---|
| API | Application Programming Interface |
| B2B | Business-to-Business |
| CDM | Conceptual Data Model |
| DCAT | Data Catalogue Vocabulary |
| DGA | Data Governance Act |
| DID | Decentralized Identifier |
| DSP | Dataspace Protocol |
| EDC | Eclipse Dataspace Components |
| EDR | Endpoint Data Reference |
| EU | European Union |
| EU-Rail JU | Europe's Rail Joint Undertaking |
| FDS | Federated Data Space |
| FMU | Functional Mock-up Unit |
| FP | Flagship Project |
| FP1 | Flagship Project 1 MOTIONAL |
| FP1-TT | Flagship Project 1 Transversal Topic |
| GA | Grant Agreement |
| HTTP | Hypertext Transfer Protocol |
| ID | Identifier |
| IDSA | International Data Spaces Association |
| IDS | International Data Spaces |
| IDS-RAM | International Data Spaces Reference Architecture Model |
| JSON | JavaScript Object Notation |
| JSON-LD | JavaScript Object Notation for Linked Data |
| MAWP | Multi-Annual Work Programme |
| MDB | Metadata Broker |
| MOTIONAL | Flagship Project 1 MOTIONAL |
| ODRL | Open Digital Rights Language |
| REST | Representational State Transfer |
| RDF | Resource Description Framework |
| SPARQL | SPARQL Protocol and RDF Query Language |
| SSI | Self-Sovereign Identity |
| TMC | Track Machines Connected |
| tmOS | TMC Central Application Hub |
| TT | Transversal Topic |
| UC | Use Case |
| VC | Verifiable Credential |
| ViF | Virtual Vehicle Research |
| WP | Work Package |
| WS | Work Stream |

# 3. Background

The European railway sector is a cornerstone of mobility across the continent, facilitating the movement of passengers and goods in an efficient, sustainable, and cost-effective manner. However, as the industry embraces digital transformation, the need for secure, interoperable, and governed data exchange has become increasingly evident.

The objective is to create a federated data ecosystem where different stakeholders — rail operators, infrastructure managers, and suppliers — can seamlessly exchange data while preserving data sovereignty, ensuring security, and maintaining a level playing field.

The International Data Spaces Association (IDSA) provides a standardized approach to trusted, secure, and decentralized data sharing through its Gaia-X [3] and International Data Spaces (IDS) compliant architecture [4]. This framework ensures that all participants in a data ecosystem (e.g., the rail domain) can share digital resources while maintaining full control over their data. An IDSA-compliant Rail Data Space aims to implement this concept within the railway industry, fostering a more integrated and data-driven ecosystem.

In this document, a demo version is presented that was developed in *WP 31 Federated Dataspaces*, which was part of the Digital Enabler Works Stream 2 of FP1 Motional or also called *Transversal Topic: Digital Enablers* (TT) as identified in Section 7.8 of the Multi-Annual Work Programme (MAWP).

Anther work package of the TT was *WP26*, which focused on creating a repository of possible use-cases from all FAs. In *WP27*, *WP28* as well as *WP29*, selected use-cases were developed further, while *WP30* discussed and refined ontologies for the selected use-cases. An overview is contextualized in Figure 1.

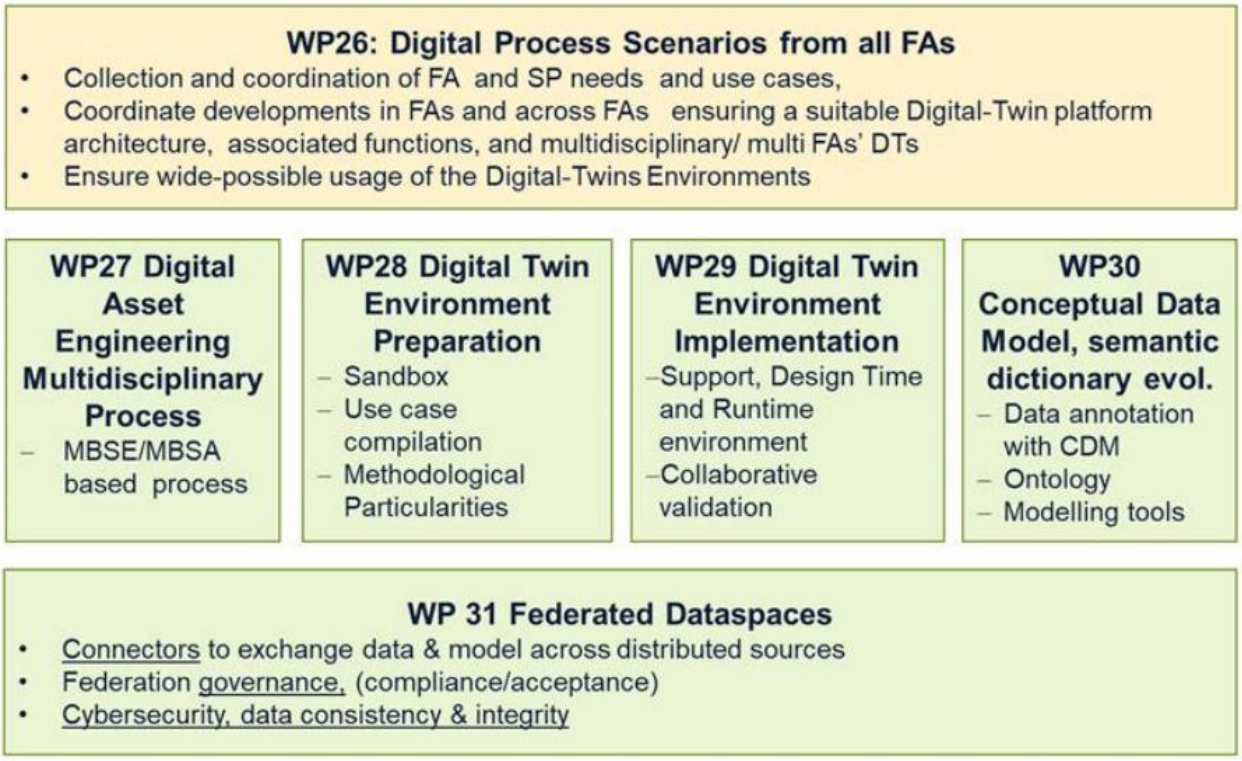



**Figure 1. Overview on FP1 work packages associated with the TT**

All these work packages are connected in the rail data space, which can deliver the data needed to run the use cases. Within this rail data space, the technologically secure and structurally sovereign networking of domain players - including operators, suppliers, maintenance companies and authorities - allows them to share and utilise their data and services based on contracts. The data itself always remains under the provider sovereignty. This is guaranteed by the federated principle of the software architecture, creating a decentralised data ecosystem with distributed rights and obligations between all participants. Thus, it will serve as basis for the implementation of use cases such as integrated ticketing, exchange of track and train diagnostic data, carbon footprint and emissions tracking, cross-company product lifecycle tracking, freight traceability and tracking.

Of course, a data space is not the only option of transferring data between participants. Table 1 shows a comparison between some commonly used methods: data space, direct Business to Business (B2B) connections via EDI or API, and a centralised platform (i.e. a data lake).

The data space combines the advantages of federated solutions and centralised approaches.

**Table 1: Comparison between Data Space, B2B, and Data Lake approaches**

| Criterion | Data Space | Direct B2B | Data Lake |
|---|---|---|---|
| Data Storage | At each party | At each party | Centralized |
| Data Sovereignty | Distributed | Distributed | Centralized |
| Single point of failure | None inherent | None inherent | Yes |
| Lock-in risk | Low | Medium–High | High |
| Discovery | Federated catalogues | None ("who knows whom") | Centralized catalogue |
| Scalability | High | Low | High, but bottlenecks |
| Trust & identity | Centralized | Bilateral trust | Centralized |
| Standardization & Principles | Centralized | Fragmented and bilateral | Centralized |
| Governance | Centralized | Fragmented and bilateral | Centralized |

Identity, credential and trust services are enabling dependencies of discovery rather than catalogue functions themselves. Identity Providers establish participant or user identity; Credential Services issue, store, present and validate Verifiable Credentials; and Trust Framework Services define recognised issuers, credential schemas, trust anchors, membership and compliance rules. These services determine which participant may query a catalogue and which credential-scoped view it receives. Discovery, however, remains a separate control-plane capability and does not itself grant access to the resource.

The MOTIONAL implementation uses "Metadata Broker" as an umbrella term for this discovery layer. Its concrete functions include provider-side catalogue publication, participant and endpoint resolution, catalogue crawling, normalisation, indexing, filtering, local caching and query APIs. This interpretation is consistent with the evolution from the earlier IDS broker role towards DSP-compatible catalogue services and with implementation patterns used in EDC based connector

A provider connector remains the authoritative source of its catalogue entries and exposes DCAT/JSON-LD descriptions and ODRL offers through the Dataspace Protocol. Catalogue crawlers or aggregation services collect only the catalogue views that the requesting participant is authorised to see and may persist a searchable local index. They do not become owners of the source metadata and do not store the underlying railway data. This distinction preserves provider control while improving cross-participant search, availability and response time.

In this deliverable, the term Metadata Broker denotes the logical discovery service through which participants publish and discover machine-readable descriptions of data and digital resources. In

the classical IDS-RAM terminology, a Metadata Broker indexes connector self-descriptions and resource metadata. In current Dataspace Protocol and EDC-based implementations, the same business capability is commonly realised through federated catalogue functions rather than through one authoritative central broker. The terms are therefore related but not identical: broker describes the service role and user-facing discovery capability, whereas federated catalogue describes the distributed architectural pattern used to implement that capability.

To develop, update and extend all necessary software features as well as to implement and test use-cases, a data space sandbox was provided by T-Systems, called the T-Systems Living Lab. Based on this implementation, there were the following key components and entities for the IDSA-compliant rail data space identified:

- **Participants** can be either data provider or data consumer. Participants are connected to the data space via connectors.
- **Offers** consist of *Assets* and *Policies*. Assets contain the meta data and a link to the actual data (which can be any kind of file, including models, instructions or service orders), while policies manage access and usage of the data (e.g. time-restricted or project-restricted), as defined by the data provider.
- **Standardised connectors** are software components for secure and trusted data exchange across all participants in the federation – using IDSA-provided sample code, reference implementations, testbed services for interoperability compliance, technical specifications, starter-kit and co-creation platform. This is presented in Deliverable *D31.4 IDSA-compliant Connectors for secure, reliable, trusted data exchange in federated data space.*
- **The Meta-data broker**, i.e. a comprehensive data catalogue, that contains machine-readable semantic descriptors of digital resources participating in the federation that are published by resource providers enabling resource discovery by resource consumers. This is presented in the current document.
- **The App-Store** as searchable repository of packaged software-components, such as compiled Digital Twin Functional Mock-up Units, common domain ontology graph developed in work package CDM, and semantic automated cross-format converters according to the common domain ontology. This is presented in Deliverable *D31.3 IDSA-Compliant App Store in federated data space*.
- **The Governance Body** defines the standards and principles on which the data space operates. It is also responsible for the definition of the commercial framework and supervises qualification and performance of the operating company
- **The Operating Company** develops the core services of the data space, e.g. registration, connectors or meta data broker. They also offer onboarding services for future participants.

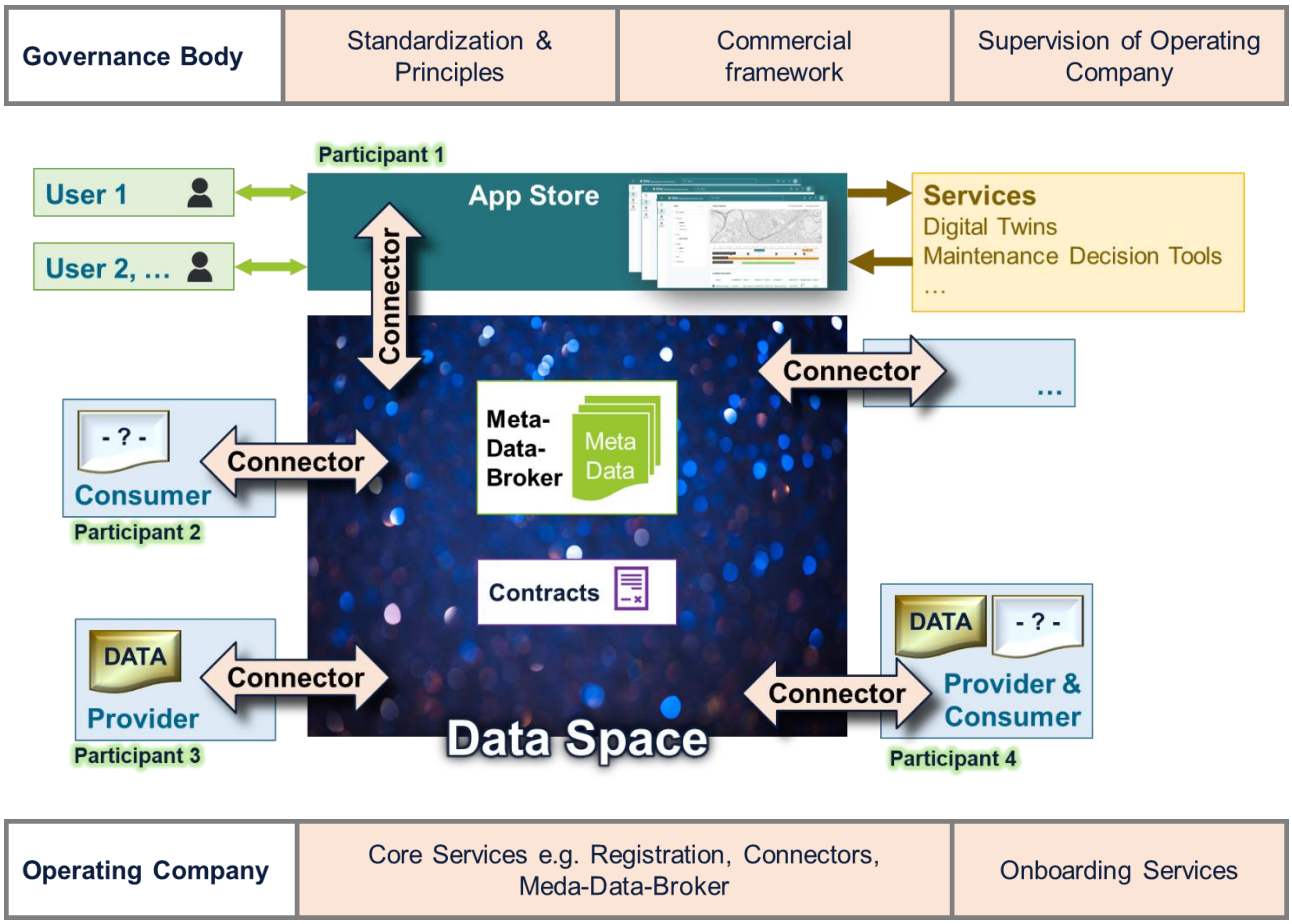



**Figure 2. Full overview of the Rail Data Space**

A full overview of the Federated Rail Data Space is given in Figure 2. It is envisioned as a federated and interoperable data ecosystem to address these challenges by facilitating a secure, transparent, and trusted data exchange. Adhering to IDSA principles and aligned with the European Data Act and EU Strategy for Data, it ensures that all participants can share data without compromising ownership rights or security.

## 4. Objective/Aim

The objective of Deliverable D31.2 is to define and demonstrate the metadata discovery and brokering capabilities required to support the Federated Rail Data Space. The work focuses on enabling participating organisations to publish, expose, discover and use machine-readable metadata-describing datasets and other digital resources across organisational boundaries, while preserving data sovereignty and supporting interoperability.

A central aim is to establish a metadata discovery approach that is consistent with the federated architecture of the Rail Data Space. Therefore, the Metadata Broker functionality is not intended to constitute a centralised repository containing the metadata nor the data of participants. Instead, it is realised through a federated catalogue capability based on Eclipse Dataspace Components (EDC), in which participating organisations maintain control over their resources and publish relevant metadata through their connector infrastructure. Catalogue information can

subsequently be discovered by authorised consumers through standardised catalogue interactions.

The objective is consequently to provide a clear separation between resource discovery, data exchange and application-level consumption. D31.2 addresses the metadata discovery layer: it enables consumers to identify relevant resources, inspect their descriptive information and understand the conditions associated with their potential use. The subsequent processes for trusted communication, contract negotiation, policy enforcement and data transfer are provided through the connector infrastructure addressed in D31.4. The user-facing consumption of discovered resources and services, including their integration into the App Store demonstrator, is addressed in D31.3. This separation ensures that metadata discovery remains a reusable enabling capability within the overall WP31 architecture.

Specifically, the objectives of D31.2 are to:

1. identify and consolidate the functional, interoperability, integration and data-sovereignty requirements for IDSA-compliant metadata discovery within the Federated Rail Data Space;
2. define an architecture for federated metadata brokering that supports decentralised metadata publication and discovery – without centralising ownership of the underlying resources;
3. specify the relevant technical components and interfaces required for catalogue publication, discovery, federation, querying and metadata management;
4. establish the use of interoperable standards and technologies – including the Dataspace Protocol (DSP), Eclipse Dataspace Components (EDC), JSON-LD, DCAT and ODRL – for machine-readable catalogue and policy information;
5. enable consumers to discover and evaluate the available resources before initiating any contract negotiation and data transfer;
6. support efficient federated discovery through catalogue crawling and local caching mechanisms where appropriate;
7. ensure that metadata discovery is technically integrated with the connector infrastructure and can provide the information required for subsequent contract negotiation and data transfer;
8. provide the metadata discovery capabilities required by the App Store demonstrator described in D31.3, thereby enabling a user-facing application to retrieve, filter and present available resources from the Federated Rail Data Space;
9. demonstrate and validate the resulting metadata discovery architecture within the MOTIONAL Living Lab environment;
10. identify remaining limitations and requirements for the further evolution and scaling of metadata discovery within the Federated Rail Data Space.

The intended outcome is a technically coherent and interoperable metadata discovery layer that can serve as a foundation for further federation of railway data and digital resources.

The approach aims to allow additional participants, resources and use cases to be integrated

without requiring a central repository for the underlying data. In this way, metadata discovery becomes an enabling capability connecting resource providers and consumers while maintaining the decentralised and sovereign character of the Federated Rail Data Space.

# 5. Methodology

The development of the metadata discovery capability followed a requirements-driven approach combining railway use-case analysis, assessment of relevant data-space standards (such as IDSA paradigms) and technologies, architectural design, and technical validation.

First, the requirements for metadata publication and discovery were derived from the railway use cases and operational scenarios considered within WP31. Particular attention was given to the heterogeneity of resources, participating stakeholders, data exchange patterns, data sovereignty, interoperability and the integration of discovery with subsequent data exchange processes.

Second, relevant reference architectures, standards and technologies were assessed in regard to their suitability for the identified requirements. The assessment has considered the International Data Spaces Reference Architecture Model (IDS-RAM), Gaia-X concepts, the Dataspace Protocol, DCAT, JSON-LD, ODRL and Eclipse Dataspace Components (EDC). The assessment focused particularly on mechanisms for decentralised metadata publication, federated catalogue discovery and integration with connector-based data exchange.

Third, the identified requirements were mapped to the selected technical capabilities and then translated into the metadata discovery architecture and specification presented in both sections 6 and 7.

The resulting architecture was subsequently checked for consistency with the other WP31 components, in particular the Living Lab environment (D31.1), the App Store (D31.3) and the connector infrastructure (D31.4).

Finally, the proposed approach was validated through implementation and demonstration within the MOTIONAL Living Lab and through the use cases and validation activities documented in Section 8 and Annex C. The validation focused on the practical feasibility of metadata publication and discovery and on the interaction between metadata discovery, policy information, contract negotiation and subsequent data transfer.

This methodology links the requirements identified from railway scenarios to the technical architecture and provides the basis for assessing whether the resulting metadata discovery capability fulfils its intended role within the Federated Rail Data Space.

The requirements presented in Chapter 6 were derived through an analysis of the resources, stakeholders, data exchange patterns and operational characteristics described in the selected railway use cases. Recurring needs identified across the use cases were consolidated into common requirement categories covering metadata publication and discovery, interoperability, data sovereignty, integration and operational aspects. These requirements subsequently informed the specification of the Metadata Broker architecture and its functional components presented in Chapter 7. Their relevance and practical applicability were then assessed against the selected use cases described in the Annexes and the implemented demonstrator. In particular, the validation activities presented in Section 8 examined whether the resulting metadata discovery capability supports the identified discovery, interoperability and integration needs in practice, thereby establishing traceability between the use-case analysis, the defined requirements, the proposed architecture and the validation results.

# 6. Requirements for IDSA-compliant Metadata Discovery in the Rail Data Space

The implementation of metadata discovery services within the Federated Rail Data Space requires a comprehensive set of requirements addressing technical, organisational, operational, and interoperability aspects. These requirements are derived from the objectives of MOTIONAL, the needs of railway stakeholders, and the architectural principles of sovereign and federated data sharing.

The requirements presented in this chapter establish the foundation for the architecture specified in section 7 and provide the criteria against which the proposed solution can be evaluated.

Table 2 provides a structured summary of the requirements explicitly stated in Section 6. Each requirement is assigned an identifier and classified according to its nature and thematic category.
The table also establishes traceability with the use cases presented in Section 8 and Annex A[1]. Priorities are assigned according to the **MoSCoW approach**, with all identified requirements classified as **Must**.

**Table 2. Consolidated metadata discovery requirements and use-case traceability**

| Requirement ID | Description | Classification | Category | Priority | Traceability to use cases |
|---|---|---|---|---|---|
| FR-01 | Participating organisations shall be able to publish machine-readable metadata describing datasets and other digital assets. | Functional | Publication | MUST | UC-1, UC-2, UC-3, UC-4 |
| FR-02 | The discovery infrastructure shall support search and retrieval operations across federated catalogue environments. | Functional | Discovery | MUST | UC-1, UC-2, UC-3, UC-4 |
| FR-03 | Discovery mechanisms shall support both human-oriented and machine-oriented interaction patterns. | Functional | Discovery | MUST | UC-1, UC-2, UC-3, UC-4 |

[1] Use-case references: UC-1 – Monitoring of Track Settlement and Identification of Single Faults in Switches; UC-2 – Maintenance Decision Tool; UC-3 – Digital Twin of Point Machine; UC-4 – Track and Positioning Regional Lines and Data Yard Automation. Description of each UC available in Section 8 and Annex A.

| | | | | | |
|---|---|---|---|---|---|
| FR-04 | The architecture shall support metadata updates and lifecycle management so that changes in ownership, availability, access conditions, technical characteristics and policy constraints can be reflected. | Functional | Lifecycle management | MUST | UC-1, UC-2, UC-3, UC-4 |
| FR-05 | Metadata discovery shall provide sufficient information for consumers to evaluate a resource before initiating access negotiation. | Functional | Resource evaluation | MUST | UC-1, UC-2, UC-3, UC-4 |
| NFR-01 | Participating organisations shall retain authority over the resources and metadata they publish, without transferring ownership to a central authority or repository. | Non-functional | Data sovereignty | MUST | UC-1, UC-2, UC-3, UC-4 |
| NFR-02 | Metadata visibility and data accessibility shall remain separate processes; access to operational data shall remain subject to policy evaluation, contract negotiation and connector-based access control. | Non-functional | Data sovereignty | MUST | UC-1, UC-2, UC-3, UC-4 |
| NFR-03 | Metadata and catalogue interactions shall use recognised machine-readable standards, including DCAT, JSON-LD, ODRL and the Dataspace Protocol, while supporting future rail-domain extensions. | Non-functional | Interoperability | MUST | UC-1, UC-2, UC-3, UC-4 |
| IR-01 | The metadata discovery layer shall integrate with the MOTIONAL sandbox environment, the App Store and the connector infrastructure. | Functional | Integration | MUST | UC-1, UC-2, UC-4 |

## 6.1. Functional Requirements

The primary purpose of the metadata discovery infrastructure is to enable participants to identify and evaluate digital resources that are made available within the Rail Data Space. To achieve this objective, the architecture must support the publication, discovery, and retrieval of metadata which describes the resources distributed across multiple organisations.

Each participating organisation shall be able to publish metadata describing datasets and other digital assets. The publication process shall enable resource providers to maintain control over the visibility and lifecycle of metadata records while ensuring that relevant information can be discovered by authorised participants.

The discovery infrastructure shall support search and retrieval operations across federated catalogue environments. Users and systems shall be able to identify resources based on descriptive attributes, resource categories, ownership information, semantic annotations, operational characteristics, and usage conditions. Discovery mechanisms shall support both human-oriented and machine-oriented interaction patterns, to facilitate automated integration scenarios (e.g., to be compatible with the App Store described in D31.3).

The architecture shall further support metadata updates and lifecycle management. As resources evolve over time, metadata records must be capable of reflecting changes in ownership, availability, access conditions, technical characteristics, and policy constraints. The discovery infrastructure must therefore support mechanisms for maintaining metadata consistency across distributed environments.

In addition, metadata discovery shall provide sufficient information to enable potential consumers to evaluate whether a resource is relevant for a specific purpose before initiating access negotiations. Metadata descriptions should therefore contain information regarding resource characteristics, applicable policies, provider identities, contractual requirements, and technical access mechanisms.

## 6.2. Data Sovereignty Requirements

Data sovereignty represents one of the fundamental principles underlying the Rail Data Space and therefore significantly influences the design of metadata discovery services.

Participating organisations must retain authority over the resources they publish and over the metadata that describes them. The discovery architecture shall not require providers to transfer ownership of metadata records to a central authority or repository. Instead, organisations shall remain responsible for creating, maintaining, and managing their own metadata assets.

The architecture must further ensure that the publication of metadata does not imply unrestricted access to the underlying data. Resource-discovery and resource-access constitute separate processes. While metadata may be discoverable by authorised participants, access to operational data shall remain subject to policy evaluation, contract negotiation, and access control mechanisms implemented through the connector infrastructure. The architecture must therefore support a clear separation between metadata visibility and data accessibility, thereby preserving the sovereignty of participating organisations.

## 6.3. Interoperability Requirements

Interoperability is essential for ensuring that metadata can be understood and processed consistently across organisational and technical boundaries. The discovery infrastructure must therefore be based on recognised standards that facilitate communication between heterogeneous systems.

Metadata representations must support machine-readable formats that enable automated processing and semantic interpretation. Resource descriptions should be compatible with established metadata standards and data space specifications to minimise integration efforts and maximise compatibility with future European data space initiatives.

The architecture has furthermore to support the use of DCAT for catalogue and dataset descriptions, JSON-LD for semantic representation, ODRL for policy expressions, and the Dataspace Protocol for communication between participating entities. These standards provide a common foundation for metadata publication and discovery and contribute to interoperability across different sectors and domains. In addition, the architecture should support future extensions and domain-specific metadata models that may emerge within the railway sector or within broader mobility data ecosystems in the future.

## 6.4. Integration Requirements

Metadata discovery services do not operate in isolation but form part of the broader Rail Data Space ecosystem. Consequently, the architecture must support seamless integration with the components specified in the other WP31 deliverables.

The discovery infrastructure must integrate with the sandbox environment defined in D31.1, enabling experimentation, testing, and validation of metadata-related capabilities. It shall further provide the discovery mechanisms required by the App Store specified in D31.3, thereby

supporting the identification and publication of applications and digital services within the ecosystem (see above-mentioned background).

Most importantly, metadata discovery shall integrate closely with the connector infrastructure specified in D31.4. Metadata publication, catalogue federation, policy enforcement, contract negotiation, and secure data exchange are closely interconnected processes that collectively support trusted data sharing. The architecture defined in this deliverable therefore assumes that metadata discovery capabilities are realised through components deployed within and alongside the connector infrastructure.

The requirements presented in this chapter establish the foundation for the metadata discovery architecture of the Federated Rail Data Space. They reflect the need to balance discoverability, interoperability, scalability, security, and data sovereignty within a distributed system. The resulting requirements provide the basis for the architectural design presented in the subsequent section 7.

# 7. IDSA-Compliant Rail Data Space Metadata Broker Specification

The metadata discovery architecture specified in this chapter translates the requirements identified in Section 6 into a concrete technical realisation for the Federated Rail Data Space. The specification is based on the principle that metadata discovery must be possible across organisational boundaries without centralising ownership of the underlying resources.

Accordingly, the Metadata Broker functionality is implemented as a federated catalogue capability using Eclipse Dataspace Components (EDC). The architecture combines provider-side catalogue publication with consumer-side catalogue discovery and, where required, catalogue crawling and local caching. This provides a distributed mechanism for resource discovery while maintaining the sovereignty of participating organisations.

The technical implementation builds on established interoperability mechanisms:

- The Dataspace Protocol provides the protocol-level interaction between participants,
- JSON-LD provides a machine-readable representation of catalogue information,
- DCAT is used for the description of catalogues, datasets and distributions,
- ODRL is used to represent usage policies,
- EDC Management APIs provide the local interfaces through which applications and services interact with the connector infrastructure.

The following sections describe the catalogue architecture, the roles of the individual catalogue components, the relevant EDC building blocks, the end-to-end discovery workflow and representative protocol messages. Together, these elements define the metadata discovery capability implemented and evaluated within the MOTIONAL Living Lab.

## 7.1. Catalogue Architecture

The catalogue interaction is based on the Dataspace Protocol (DSP) and EDC control-plane APIs. The relevant technical concepts are (Table 3):

**Table 3. Relevant Concepts**

| Layer | Purpose |
|---|---|
| HTTPS / REST | Transport binding for protocol and management interactions |
| Dataspace Protocol | Interoperable participant-to-participant protocol for catalogue access, contract negotiation and transfer process coordination |
| JSON-LD | Machine-readable representation format for catalogue and policy information |
| DCAT | Vocabulary used to describe catalogues, datasets and distributions |
| ODRL | Vocabulary used to express permissions, constraints, obligations and usage policies |
| DID / Participant ID | Identifier of a dataspace participant or connector identity |
| EDC Management API | Local API used by applications or UIs to interact with the participant's own connector |

### 7.1.1. Federated Catalogue Roles

The EDC federated catalogue consists of two main logical roles:

1. **Catalogue Node:** publishes the assets offered by a participant. It makes the participant's data offers discoverable to other authorized participants in the dataspace. Technically, the Catalogue Node does not act as a classical data repository. It provides an index of assets and pointers to the actual resources, which may reside in cloud storage, databases, applications or other backend systems controlled by the provider.

2. **Catalogue Crawler / Catalogue Cache:** The Catalogue Crawler discovers catalogue information published by other participants. Instead of querying every connector in real time for each user request, the crawler periodically collects accessible catalogue entries from other participants and updates a local, query-able catalogue cache. This enables scalable resource discovery while preserving the decentralized nature of the dataspace.

## 7.2. Core EDC Components for Metadata Brokering

### 7.2.1. Management API (Control Plane)

**Table 4. Management API**

| Endpoint | Method | Purpose |
|---|---|---|
| /api/management/assets | POST | Register new asset with metadata |
| /api/management/policy definitions | POST | Create usage policies |
| /api/management/contract definitions | POST | Link assets to policies |
| /api/management/assets/{id} | GET | Retrieve asset details |
| /api/management/assets/{id} | DELETE | Remove asset |

**Asset Registration Example**

```
POST /api/management/assets
{
 "id": "rail-timetable-asset-001",
 "properties": {
  "name": "Regional Train Timetable Dataset",
  "domain": "rail",
  "resourceType": "timetable",
  "version": "2026-05",
  "keywords": ["rail", "timetable", "operations"]
 },
 "dataAddress": {
  "type": "HttpData",
  "baseUrl": "https://provider-api.../timetables"
 }
}
```

### 7.2.2. Control Plane (Contract & Policy Engine)

**Table 5. Contract and Policy Engine**

| Component | Responsibilities |
|---|---|
| Asset Management | Metadata storage, versioning, search indexing, public/private property separation |
| Policy Engine | ODRL policy evaluation, constraint checking (leftOperand operator rightOperand), DID-based verification |
| Negotiation Engine | Dual-ledger state machine (REQUESTED → FINALIZED), offer/counteroffer, VC validation |
| Transfer Manager | Transfer lifecycle orchestration, EDR token management, state machine coordination |

### 7.2.3. DSP Endpoint (Catalogue Node)

Federated catalogue publishing and protocol-level interoperability. Exposes the organization's catalogue via the Dataspace Protocol standard, converting internal assets to DCAT format with ODRL policies. Figure 3 illustrates the Catalogue Query Flow.

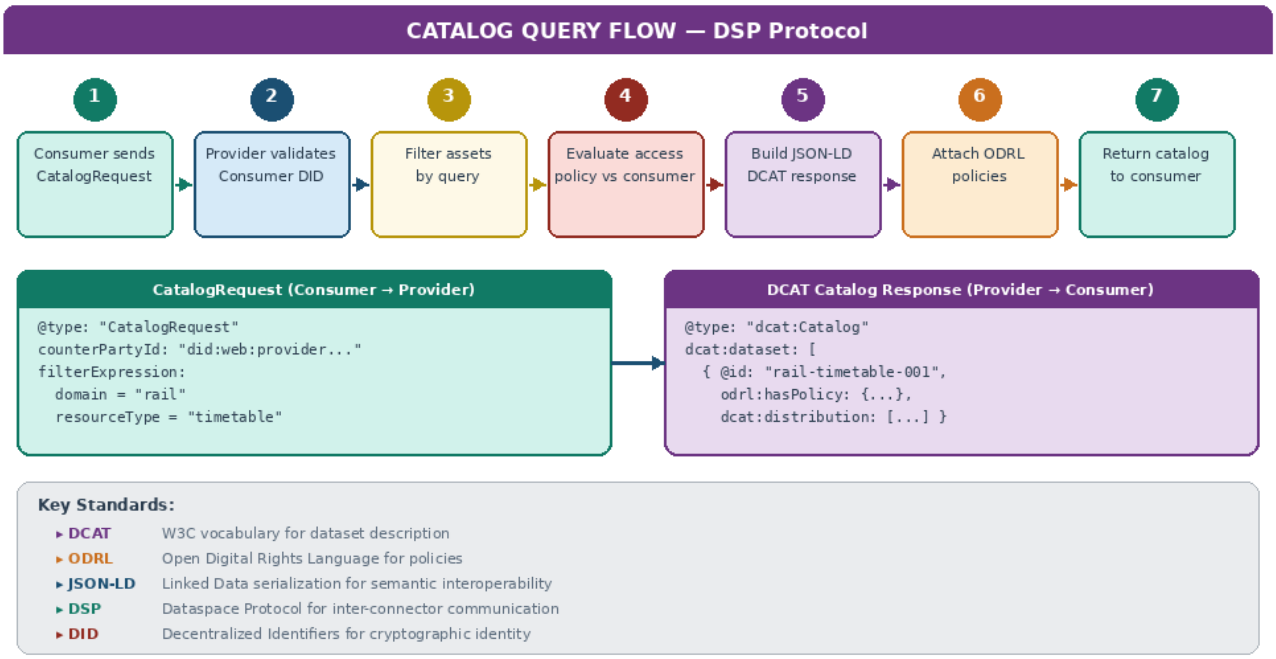



**Figure 3. Catalogue Query Flow**

### 7.2.4. Catalogue Crawler & Local Cache

Consumer-side metadata aggregation through federated discovery. The crawler periodically polls known provider connectors (configurable, defaults to 120s), parses and then caches DCAT responses locally for sub-second searches. Figure 4 illustrates the Federated catalogue crawling workflow.

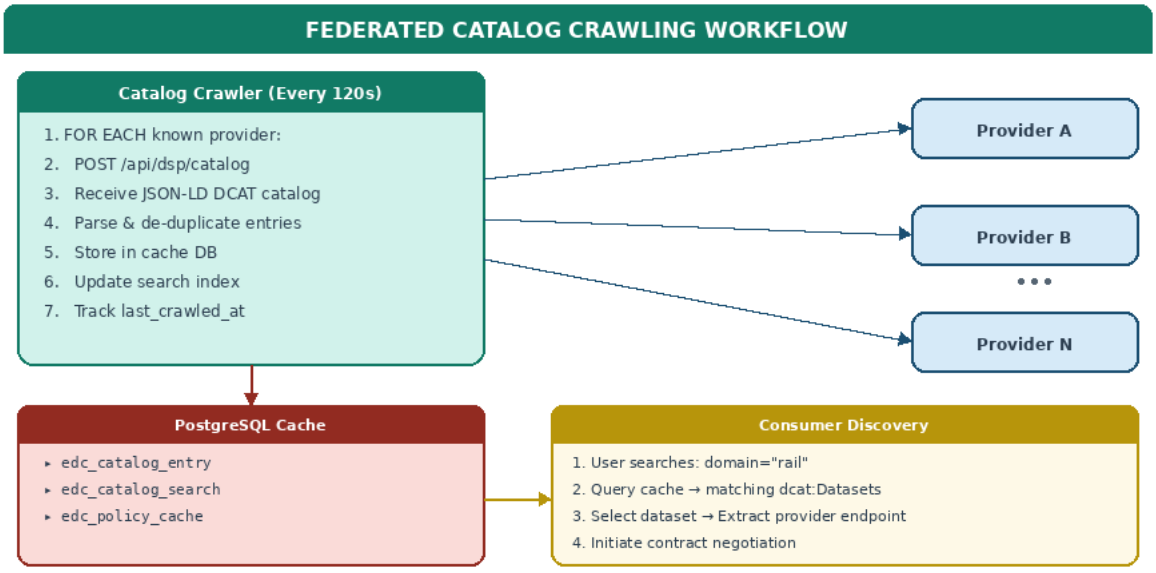



**Figure 4. Federated Catalogue Crawling Workflow**

### 7.2.5. Data Plane (Transfer Execution)

Handles actual data transfer and access control enforcement via EDR (Endpoint Data Reference) tokens — short-lived JWTs scoped to specific contract agreements (see Figure 5).

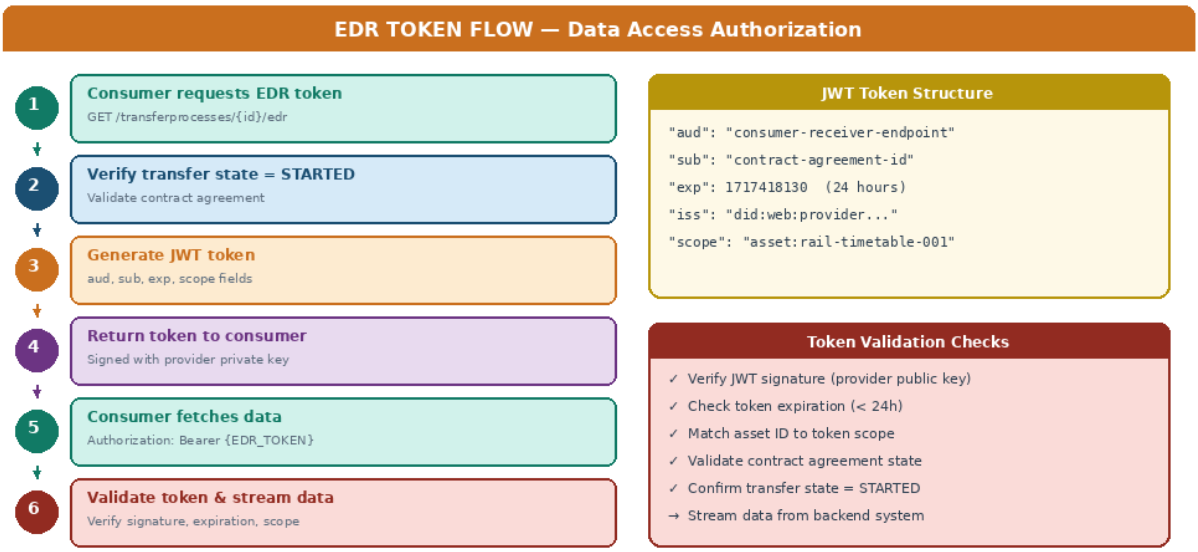



**Figure 5. Data Access Authorization**

### 7.2.6. State Persistance (PostgreSQL)

Persistence is required because the metadata discovery and connector workflows are stateful and must survive process restarts, transient network failures and asynchronous interactions. PostgreSQL stores operational records for locally managed assets, policy definitions, contract definitions and agreements, transfer processes, catalogue crawl results and searchable catalogue-cache entries. For each cached catalogue record, the implementation should retain the resource

identifier, source participant and endpoint, the authorised DCAT/JSON-LD representation, associated ODRL offers, retrieval and update timestamps, crawl status, and a version or fingerprint where available. For negotiations and transfers, it stores identifiers, counterparties, state transitions, agreement references and timestamps; secrets and short-lived credential material should remain in dedicated secure stores rather than in catalogue records.

Persistence supports traceability by preserving provenance and lifecycle evidence: operators can determine where a catalogue entry originated, when it was last retrieved, which authorised view was indexed, and which state transitions occurred during negotiation or transfer. It supports discovery by providing a queryable local index, enabling filtering and cross-provider search without contacting every provider for each user query. Cached entries are not authoritative copies: the provider catalogue remains the source of truth, and refresh, expiry or invalidation rules are needed to manage stale or withdrawn offers. Database transactions and atomic state transitions ensure that crawler checkpoints, catalogue updates and workflow states remain consistent after failures.

All operational state persists across restarts with atomic transitions and audit trail support (for details, see Figure 6).

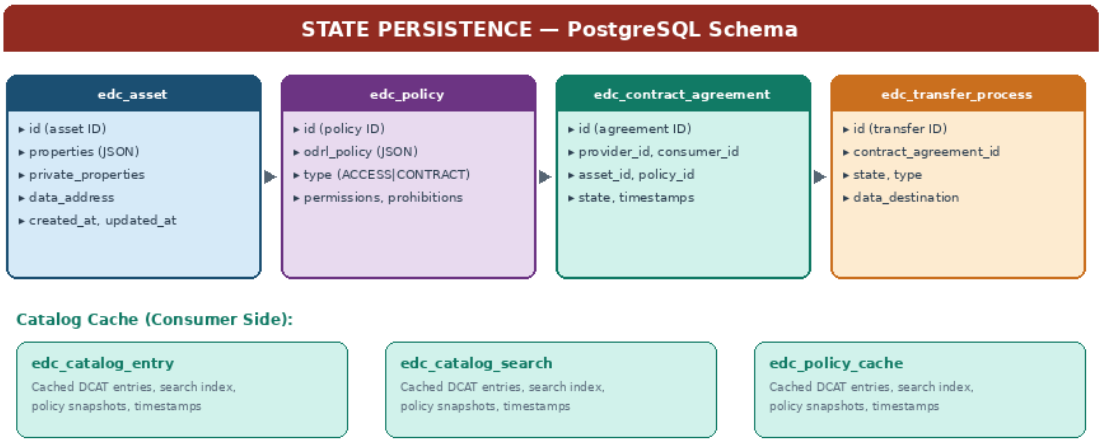



**Figure 6. PostgreSQL Schema**

## 7.3. End-to-End Workflow

The end-to-end workflow covers the main steps through which users discover the available metadata and subsequently access the relevant data assets.

1. **Asset Registration:** Provider registers asset metadata, access policy, contract policy, and contract definition via the Management API. Private properties remain internal and are never exposed in catalogue responses.
2. **Catalogue Publishing:** The DSP endpoint automatically exposes registered assets as a DCAT catalogue. Access policies are evaluated at query time – only authorized consumers see matching assets.
3. **Federated Discovery:** Consumer's catalogue crawler periodically polls provider DSP endpoints, caches results in PostgreSQL, and builds a local search index. Then, sers query the cache for sub-second discovery.

4. **Contract Negotiation**: Consumer initiates negotiation via DSP. Provider evaluates consumer's Verifiable Credentials against contract policy constraints. The state machine transition as follows: REQUESTED → OFFERED → ACCEPTED → AGREED → VERIFIED → FINALIZED.
5. **Transfer & Data Access:** Consumer initiates transfer, provider generates a short-lived JWT (EDR token) scoped to the specific asset and agreement. Consumer fetches data using the token; provider validates signature, expiration, and scope before streaming.

For an overview of the end-to-end workflow, please refer to Figure 7.

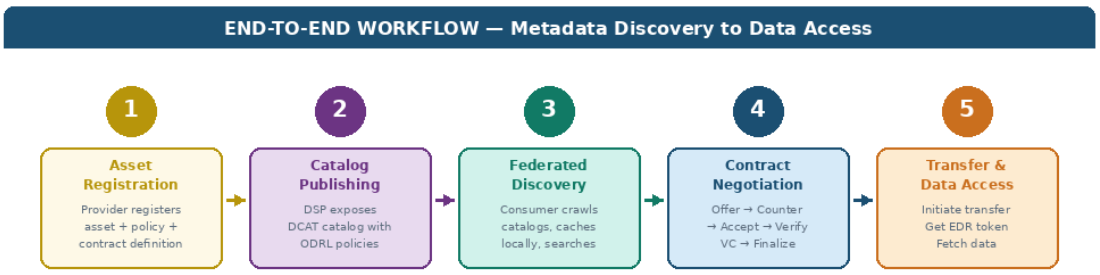



**Figure 7 Metadata Discovery to Data Access**

## 7.4. Protocol Examples

### 7.4.1. Catalogue Request

A simplified catalogue request from a consumer connector to a provider connector:

```
{
 "@context": {
  "@vocab": "https://w3id.org/edc/v0.0.1/ns/"
 },
 "@type": "CatalogRequest",
 "counterPartyAddress":
  "https://provider-connector.rail-dataspace.example/protocol",
 "counterPartyId":
  "did:web:provider.rail-dataspace.example",
 "protocol": "dataspace-protocol-http",
 "querySpec": {
  "offset": 0,
  "limit": 50
 }
}
```

### 7.4.2. Catalogue Response

The response is a machine-readable catalogue containing metadata, contract offers, policy information and technical references. It does not contain the actual data payload.

```
{
 "@id": "catalogue-provider-a",
 "@type": "dcat:Catalog",
 "participantId": "did:web:provider.rail-dataspace.example",
 "dcat:dataset": [{
```

```
  "@id": "rail-timetable-asset-001",
  "@type": "dcat:Dataset",
  "properties": {
    "name": "Regional Train Timetable Dataset",
    "contenttype": "application/json",
    "domain": "rail",
    "resourceType": "timetable",
    "updateFrequency": "daily",
    "keywords": ["rail","timetable","operations","mobility"]
  },
  "odrl:hasPolicy": {
    "@type": "odrl:Offer",
    "odrl:permission": [{
      "odrl:action": { "@id": "odrl:use" },
      "odrl:constraint": [{
        "odrl:leftOperand": "Membership",
        "odrl:operator": { "@id": "odrl:eq" },
        "odrl:rightOperand": "RailDataSpaceParticipant"
      }]
    }]
  },
  "dcat:distribution": [{
    "dct:format": "application/json",
    "dcat:accessService": {
      "dct:terms": "dataspace-protocol-http",
      "dcat:endpointUrl":
        "https://provider-connector...example/protocol"
    }
  }]
 }]
}
```

### 7.4.3. Filtered Catalogue Request

A consumer application may search only for specific resources. A filtered request using *filterExpression* narrows results to matching entries visible to the requesting participant:

```
{
 "@type": "CatalogRequest",
 "counterPartyAddress":
   "https://provider-connector.rail-dataspace.example/protocol",
 "counterPartyId":
   "did:web:provider.rail-dataspace.example",
 "protocol": "dataspace-protocol-http",
 "querySpec": {
   "offset": 0,
   "limit": 10,
   "filterExpression": [
     {
       "operandLeft":
         "https://w3id.org/edc/v0.0.1/ns/domain",
       "operator": "=",
       "operandRight": "rail"
     },
```

```
    {
      "operandLeft":
        "https://w3id.org/edc/v0.0.1/ns/resourceType",
      "operator": "=",
      "operandRight": "timetable"
    }
  ]
 }
}
```

*Note: The response for this request above would contain only catalogue entries visible to the requesting participant and matching the query criteria.*

# 8. Use-Case-Based Validation of Metadata discovery and Demonstrator

The metadata discovery capabilities specified in this deliverable were provided against concrete railway use cases rather than as an isolated technical component. The use cases documented in ANNEX A provide representative scenarios for assessing what information needs to be discoverable, how resources are related to their potential consumers, and which requirements arise for the underlying Federated Data Space. From the perspective of D31.2, these use cases therefore provide an important validation basis for the Metadata Broker and its integration with the connector infrastructure.

The use case analysis covers four scenarios:

- “Monitoring of Track Settlement and Identification of Single Faults in Switches”,
- “Maintenance Decision Tool”,
- “Digital Twin of Point Machine”, and
- “Track and Positioning regional Lines and Data Yard Automation”.

The scenarios cover different types of resources, stakeholders and data exchange patterns, ranging from static datasets and periodically updated information to event-driven and real-time data. This diversity is relevant for metadata discovery because the catalogue must provide sufficient information for consumers to identify the nature, origin, format and intended use of available resources before initiating an exchange.

The detailed use-case descriptions, data requirements and implementation status are all provided in ANNEX A.

## 8.1. Use-Case Requirements Relevant to Metadata Discovery

The “Monitoring of Track Settlement and Identification of Single Faults in Switches” use case represents a predictive maintenance scenario. It requires different categories of input, including forecast information, vehicle-related data, track geometry, maintenance actions, measurements and static infrastructure and vehicle parameters. The scenario therefore illustrates that metadata discovery needs to support the identification and differentiation of heterogeneous resources which may originate from different providers and have different formats, update characteristics and intended uses. The use case was implemented as a demonstrator within the Federated Data Space, although with reduced functionality to focus on the underlying framework technology and IT infrastructure.

The “Maintenance Decision Tool” demonstrates a subsequent stage of the same data flow. It combines asset information, maintenance records, condition-monitoring data and prediction results and, therefore, illustrates the need to discover resources that can be associated with specific railway assets and subsequently consumed by different systems. In the MOTIONAL demonstrator, turnout master data is synchronised with the tmOS Marketplace, while prediction results generated by external analytics services can be transferred back to the asset-management environment. The integration was implemented and demonstrated as part of the Federated Data Space demonstrator.

The “Digital Twin of Point Machine” use case extends the requirements towards digital-twin-

related resources. It considers diagnostic events, health scores, residual useful life, operational states, real-time measurements, simulation scenarios and FMU-based evidence. From a metadata perspective, the scenario demonstrates the need to describe heterogeneous digital resources and make their availability discoverable while keeping the underlying resources under the control of the respective provider. The use case defines the relevant roles and requirements, but a full implementation within the Federated Data Space was not realised, though it is identified for further development in Wave 2.

The "Track and Positioning regional Lines and Data Yard Automation" use case introduces dynamic and potentially real-time information, including vehicle position records, vehicle context, yard track topology and regional track-line topology. It demonstrates the applicability of the Federated Data Space beyond the predictive maintenance scenarios and highlights the need to discover resources whose availability and update characteristics may be event-driven. The use case was progressively validated through laboratory integration and end-to-end demonstrations, including interoperability testing with provider and consumer connectors and validation of on-demand retrieval mechanisms.

Taken together, these use cases demonstrate that the Metadata Broker must support discovery across heterogeneous resource types, providers and consumption scenarios. Relevant metadata must allow consumers to identify a resource, understand its characteristics and determine whether it is suitable for a particular application or workflow.

At the same time, the use cases confirm that metadata discovery is only one stage of the overall process. Once a suitable resource has been identified, the connector infrastructure is required for contract negotiation, policy enforcement and data transfer. This distinction is reflected in the architecture specified in Section 7.

## 8.2. Relationship between the Use Cases and the Metadata Broker

The use cases provide the operational context in which the Metadata Broker is required and therefore represent an important basis for assessing its relevance. They specify heterogeneous resources, providers, consumers and data exchange patterns that need to be made discoverable before data can be accessed or processed. In this sense, the use cases define the information that a consumer needs to identify and assess a potentially relevant resource.

Conversely, the Metadata Broker provides the discovery capability that connects these use-case requirements with the distributed resources available in the Federated Rail Data Space. It does not execute the use cases or provide access to the underlying data itself. Instead, it exposes machine-readable metadata describing available assets, their characteristics, providers, distributions and applicable policies. A consumer can therefore use the catalogue information to identify suitable resources before initiating the subsequent connector-based negotiation and data transfer processes.

The aforementioned four use cases illustrate different aspects of this relationship:

1. The predictive-maintenance scenario requires discovery of heterogeneous infrastructure, vehicle and measurement data;
2. the Maintenance Decision Tool requires discovery and exchange of asset and prediction-related information;

3. the Digital Twin scenario extends discovery towards simulation and diagnostic resources;
4. and the regional positioning scenario introduces dynamic and event-driven resources.

Together, they demonstrate that metadata discovery must remain sufficiently generic to support different resource types and exchange patterns while providing sufficient descriptive information for consumers to assess their relevance.

These use cases validate therefore the Metadata Broker, primarily at the level of its intended function: enabling the identification and evaluation of distributed resources as a prerequisite for controlled data exchange. The demonstrator subsequently validates this relationship technically by integrating metadata discovery with the connector infrastructure and the App Store.

## 8.3. Demonstrator-Based Validation

The metadata discovery capabilities were validated as part of the wider WP31 Federated Rail Data Space demonstrator. As described in D31.3, the WP31 demonstrator was expected to combine three key capabilities: standardised connectors for secure and trusted data exchange, a metadata broker providing machine-readable descriptions of digital resources and enabling resource discovery, and an App Store providing a searchable repository and user-facing interface for software components and use cases.

The resulting demonstrator was presented during the *FLAGSHIP PROJECT 1 MOTIONAL DIGITAL FOUNDATION DEMONSTRATION & VALIDATION EVENT* on 29 April 2026. It included working connectors, the metadata broker and an implemented App Store with two available use cases. A subsequent Validation Event was held on 7 May 2026.

During the demonstration, the interaction between metadata publication, resource discovery, contract negotiation and data transfer was demonstrated. Data offers containing metadata and links to the underlying data as well as access and usage policies were published. Once an offer was published, it could be searched for by a consumer. The consumer could then provide the required credentials, specify a destination for the data and select an applicable policy. Following contract negotiation, the data transfer was initiated automatically. This demonstrated the role of metadata discovery as the entry point to the subsequent connector-based exchange workflow.

The demonstrator further showed the interaction with the implemented use cases. The “Monitoring of Track Settlement and Identification of Single Faults in Switches” use case was presented through the App Store, while the resulting output was subsequently transferred to Zentrak as the Maintenance Decision Tool. Thus, the demonstrator showed an end-to-end workflow from data publication and discovery through connector-based exchange and Digital Twin execution to maintenance decision support.

The following description is retained from D31.3 (as well as D31.4) because it formed part of a joint effort within WP31:

As described in FP 1 Maturity Check Point 7 Supporting Documents, it was expected that a demonstrator with a TRL of 7 was developed within WP31. Therefore, certain capabilities had to be implemented:

- **Standardised connectors**, which are software components for secure and trusted data exchange among participants in the federation, using IDSA provided sample code, reference implementations, testbed services for interoperability compliance, technical specifications, a starter kit and a co-creation platform. This is presented in Deliverable *D31.4 IDSA-compliant Connectors for secure, reliable, trusted data exchange in federated data space.*
- **Meta-data broker**, i.e. a comprehensive data catalogue that contains machine-readable semantic descriptors of digital resources participating in the federation and are published by resource providers enabling resource discovery by resource consumers. This is presented in Deliverable *D31.2 IDSA-compliant meta-data broker and discovery services in federated data space.*
- **App-Store** as a searchable repository of packaged software components such as compiled Digital Twin Functional Mock-up Units, the common domain ontology graph developed in work package CDM, and semantic automated cross-format converters according to the common domain ontology. This is presented in the current document.

The resulting demonstrator was then presented to the public during the *FLAGSHIP PROJECT 1 MOTIONAL DIGITAL FOUNDATION DEMOSTRATION & VALIDATION EVENT* on 29th April 2026 and later validated by two external validators during the Validation Event for WP31 on 7th May 2026.

A demonstrator of the rail data space including working connectors, metadata broker and an implemented app store with two available use cases was demonstrated during the FLAGSHIP PROJECT 1 MOTIONAL DIGITAL FOUNDATION DEMONSTRATION & VALIDATION EVENT on 29th April 2026.

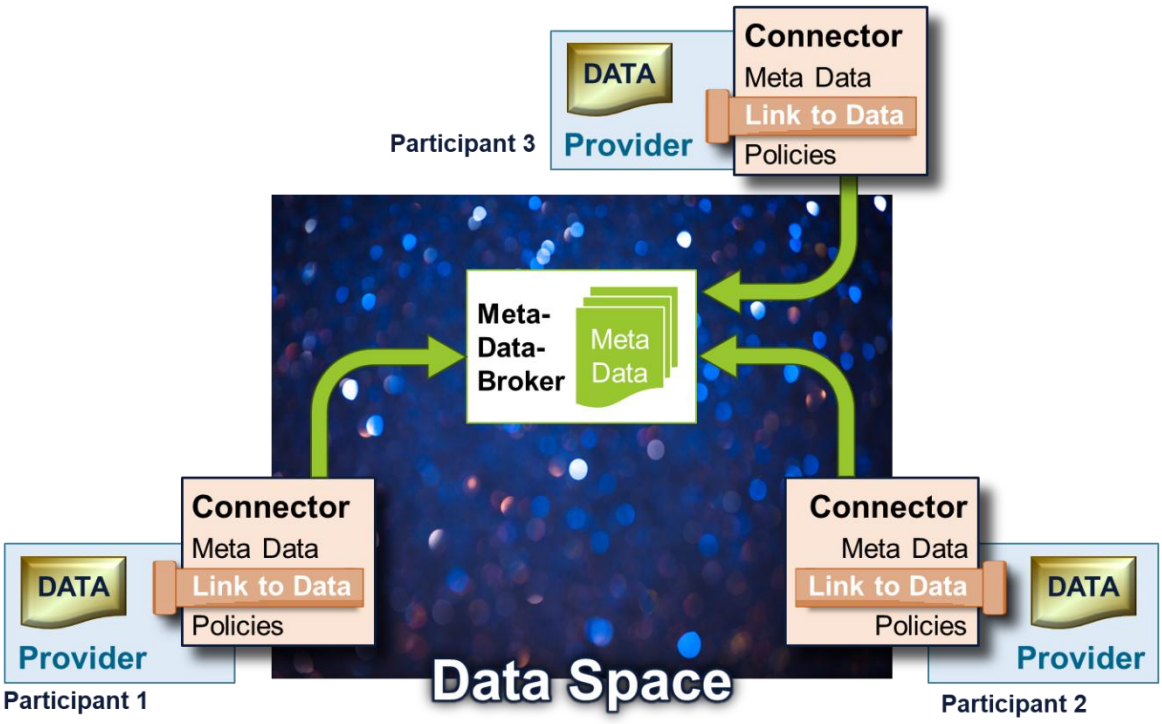



**Figure 8. Publishing of data offers to meta data broker**

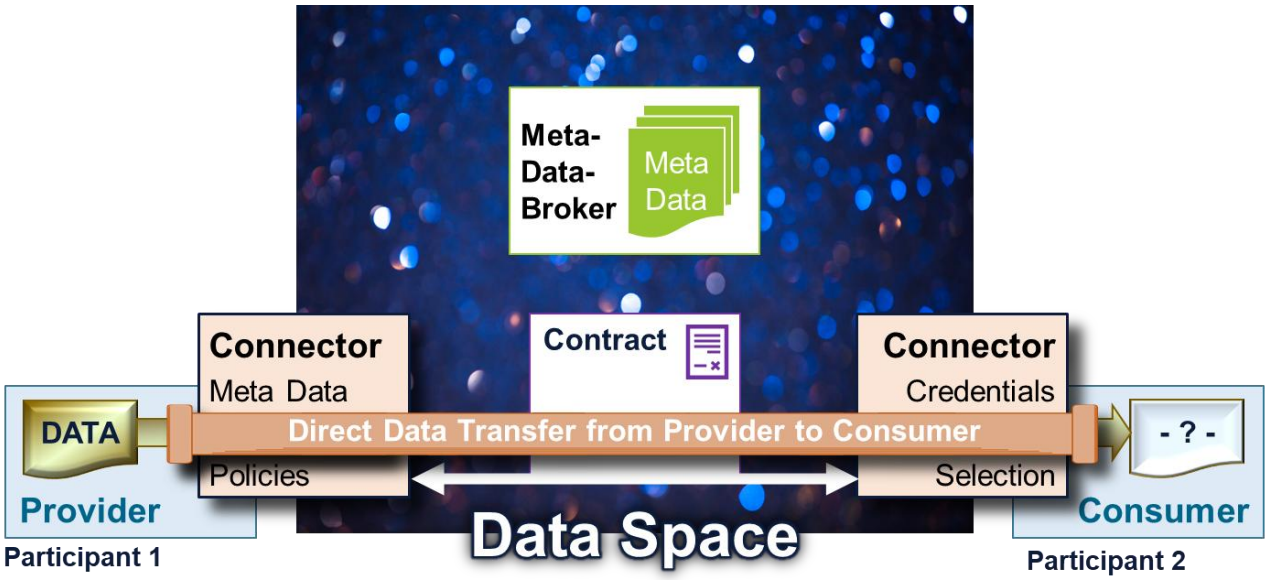



**Figure 9. Secure data transfer through the connector.**

There, an introductory video was presented, which was originally created and shown at the InnoTrans 2024. Then, an overview of the data space was given, including an introduction of participants and a description of connectors, the metadata broker and the app store. Next, the question of how to share data was answered by introducing data offers. Once an offer is published, it can be searched for by a consumer, providing their credentials, a destination for the offered data to be transferred to and by selecting one of the offered policies. Then, a contract is digitally signed and the data transfer is started automatically as shown in Figure 9.

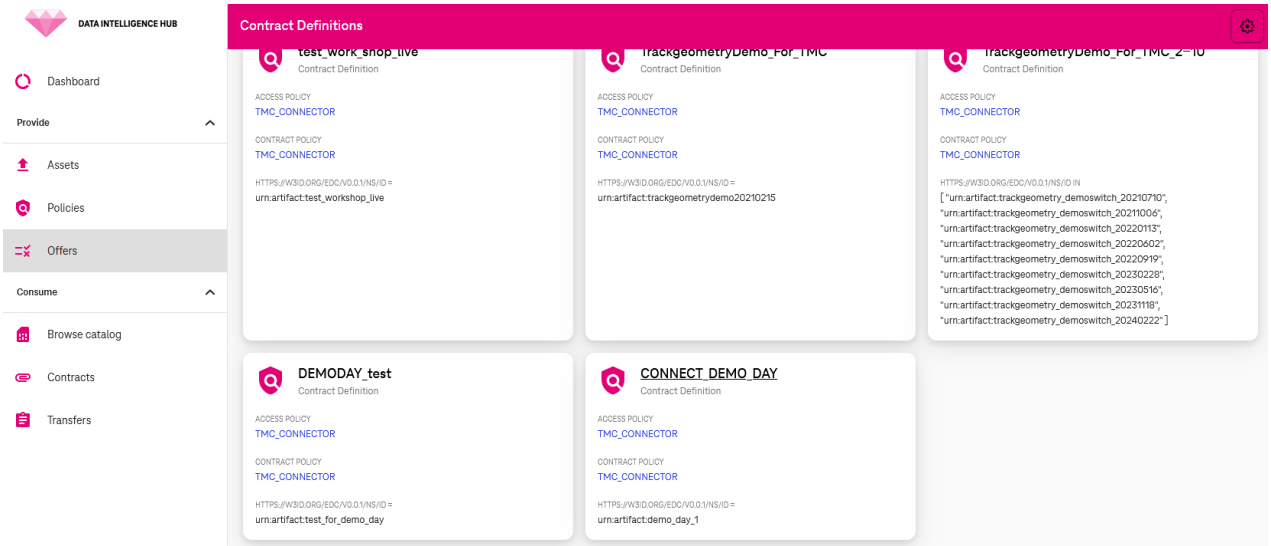



**Figure 10. Screenshot of the Living Lab sandbox environment including a created data offer.**

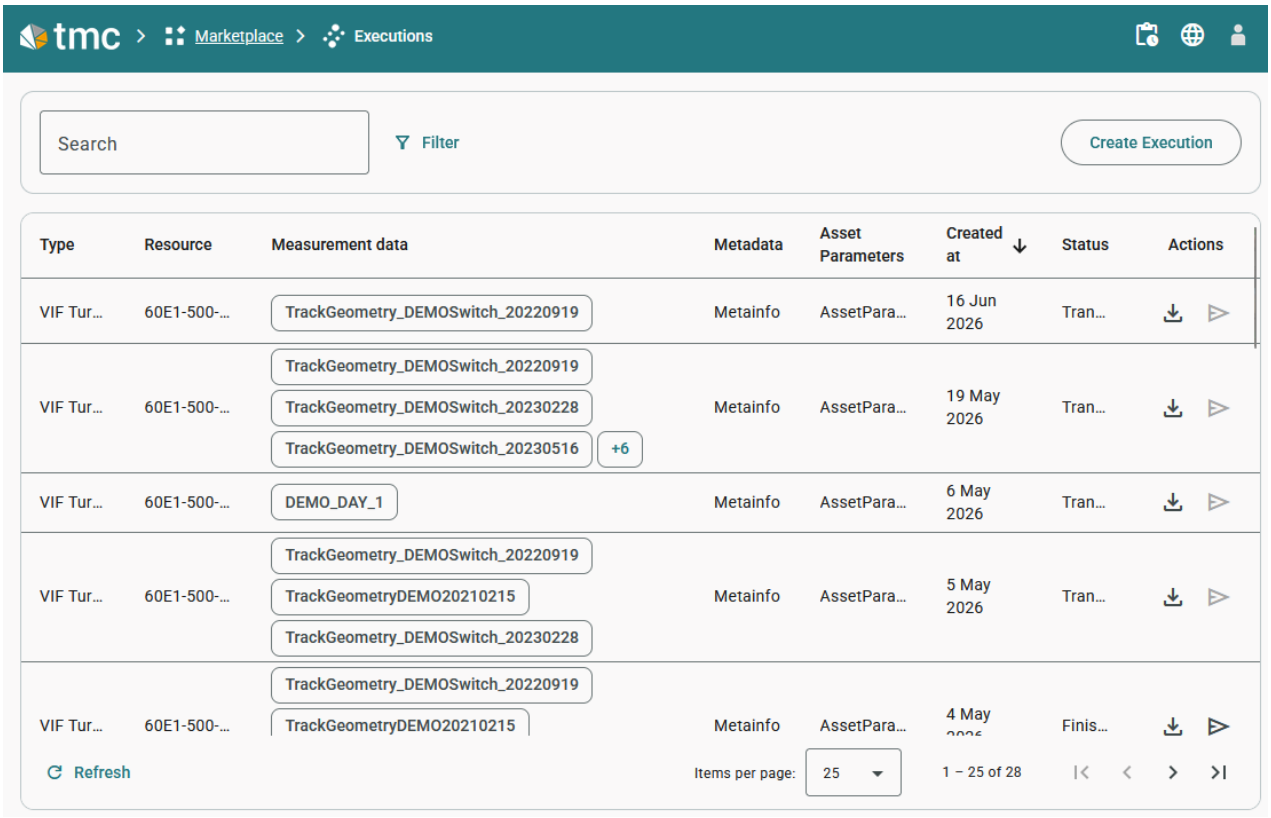



**Figure 11. Screenshot of the App-Store including executed use-cases.**

Using a video of the Living Lab sandbox environment, the creation of offers containing assets (metadata and link to data) and policies (access and usage) was demonstrated. A screenshot is shown in Figure 10 with the created data offer.

Next, the example use-case *Monitoring of Track Settlement and Identification of Single-Faults in Switches*, previously discussed in subsection 8.1, was presented. Then, a pre-recorded video showed the implementation in the app-store. The use-case was executed using the front-end of the app store and the results were then shown to be directly transferred to Zentrak, the *Maintenance Decision Tool*, also introduced in subsection 8.1.

From the perspective of D31.2, the significance of this demonstration is that the Metadata Broker was not validated only as an isolated catalogue component. Its functionality was demonstrated as part of an end-to-end workflow in which metadata and policy information enabled a consumer to identify and select a resource before the connector-based contract negotiation and transfer processes were initiated. The demonstrator therefore provides practical evidence that the metadata discovery layer fulfils its intended role within the overall WP31 architecture.

Based on the demonstrator presented during the demonstration event, a separate Validation Event was held on 7. May 2026. There, the goal was to demonstrate TRL 6 “Technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)”. According to BRIDGE2HE H2020-101005071[2], this means that “the prototype has to be demonstrated in a real environment, so to confirm the engineering is

[2] BRIDGE2HE. (2022). Guiding notes to use the TRL self-assessment tool (Grant Agreement No. 101005071). Horizon Europe NCP Portal. Retrieved September 16, 2026, from https://horizoneuropencpportal.eu/sites/default/files/2022-12/trl-assessment-tool-guide-final.pdf

feasible". In case of a software, it must be a "Beta version of the software functionalities tested by selected end-user under a control mode".

To test the functionalities, four validators were invited to test the data space. They were given access to the tmOS Marketplace with 2 implemented use cases: the "Monitoring of Settlement and Identification of single Faults in switches" and the "Maintenance Decision Tool" use case, along with an onboarding session consisting of a presentation and a Q&A session. Then they were given a deadline of two weeks to test the capabilities. They were able to successfully use the demonstrator, proofing TRL 6. Afterwards, they were asked to fill out a questionnaire. Of the four validators, two sent responses concurring that they were able to successfully use the demonstrator, proofing that TRL 6 was achieved. The detailed responses can be found in Annex C.

The questionnaire responses, presented in detail in Annex C, show that the validators view the Federated Data Space and App Store primarily as a strategic enabler for the rail sector rather than a merely technical tool. Both participants rated the relevance of the proposed Data Space to their organisation as moderate. The expected impact was primarily associated with maintenance and reliability, data integration and interoperability, and cross-border harmonisation. The most valuable benefit identified was easier access to data and services combined with secure interoperability between systems, reflecting the broader ambition of the Federated Data Space to overcome data fragmentation across the rail value chain. At the same time, the validators indicated that the technology is not yet ready for large-scale deployment: expected adoption timeframes range from less than one year to more than three years, and financial return on investment as well as legal and governance compliance were named as the primary barriers to adoption. Trust-building elements such as guarantees of data sovereignty, auditability and certification mechanisms, were consistently highlighted as prerequisites for wider participation. Overall, the validation confirms that, from a macroeconomic perspective, industry stakeholders recognise the potential of data space technology to reduce costs, harmonise cross-border operations and enable new digital services for the rail sector. However, regulatory clarity, demonstrated technical maturity and clear economic value are seen as the critical success factors that still must be addressed before broader industry adoption can take place.

## 8.4. Validation Results and Implications for the Metadata Broker

The Validation Event assessed the demonstrator against the TRL objective of demonstrating technology in a relevant environment. The validators received access to the tmOS Marketplace and the two implemented use cases and were given an onboarding session followed by a two-week testing period and questionnaire.

Although the questionnaire addressed the Federated Data Space and App Store as a whole, rather than the Metadata Broker as an isolated component, several findings directly support the requirements identified for metadata discovery. The validators identified easier access to data and services and secure interoperability between systems as key benefits. The expected application areas included maintenance and reliability as well as data integration and interoperability. These findings reinforce the relevance of a discovery layer that makes distributed resources identifiable and accessible through standardised mechanisms.

The technical validation highlighted the importance of access control and data sovereignty. The

responses identified strict purpose limitation, auditability, the ability to revoke access, anonymisation and intellectual-property protection as relevant guarantees. Interoperability was associated with established railway and data-space standards, including TSI, ISO/CEN/CENELEC, Asset Administration Shell and IDS/Gaia-X.

From the Metadata Broker perspective, these results confirm three principal requirements:

- First, metadata discovery must provide sufficiently informative and structured descriptions to enable users and applications to identify suitable resources across organisational boundaries.
- Second, metadata discovery must remain integrated with the policy and connector mechanisms that govern subsequent access.
- Third, the discovery must remain compatible with the interoperability and sovereignty principles required for broader adoption of the Federated Rail Data Space.

The validation also identified technical maturity, regulatory backing, clear economic value, auditability and transparent trust mechanisms as important prerequisites for wider deployment. At the same time, the validators indicated that the technology was not yet ready for unrestricted large-scale deployment.

The analysis also identifies clear areas for future development. Particularly, use cases involving real-time and event-driven data require further investigation of the corresponding connector (see D31.4) and discovery requirements. Similarly, scaling the catalogue federation, onboarding additional participants, strengthening semantic interoperability and establishing mature governance and trust mechanisms remain steps towards operational deployment readiness.

These aspects are consistent with the limitations identified in D31.3, where the use-case analysis notes that the sandbox connector technology could not yet fulfil all prerequisites for the more demanding scenarios and identifies real-time data exchange as an area for further Wave 2 and Wave 3 development.

## 8.5. Interaction with other Flagship Projects

FP1-MOTIONAL WP31 interacted with other Europe's Rail Flagship Projects. The links were established with *FP3 – IAM4RAIL* and *FP6 – FutuRe*, whose use cases are also relevant to the Federated Rail Data Space and the metadata discovery capabilities developed in WP31. In addition, interaction with FP5 addressed knowledge exchange and the planned onboarding of additional participants to the Living Lab.

The detailed interactions, related use cases and objectives are documented in ANNEX A and ANNEX B.

# 9. Conclusions

The objective of D31.2 was to define and demonstrate an IDSA-compliant approach for metadata publication, brokering and discovery within the Federated Rail Data Space. The work addressed this objective through a requirements-driven analysis of railway use cases, an assessment of relevant data space standards and technologies, the definition of a federated catalogue architecture, and implementation and validation within the MOTIONAL Living Lab.

The results show that the identified metadata discovery requirements can be addressed through a federated catalogue approach based on Eclipse Dataspace Components. Metadata can be published through participant connectors and discovered through standardised catalogue interactions, while the underlying data remains under the control of the respective provider. The combination of the Dataspace Protocol, JSON-LD, DCAT and ODRL provides the basis for machine-readable catalogue and policy information. The architecture further separates discovery from contract negotiation and data transfer, thereby maintaining the distinction between identifying a resource and accessing the resource itself.

The use case analysis and demonstrator validation provide practical evidence for this approach. The use cases demonstrated the need to discover heterogeneous resources across different providers and exchange patterns, while the demonstrator showed the integration of metadata discovery with the connector infrastructure and the App Store. In particular, the demonstrated workflow from metadata publication and discovery through policy selection, contract negotiation and subsequent data transfer confirms the intended role of the Metadata Broker as an enabling discovery layer within the Federated Rail Data Space.

The results indicate that metadata discovery is a necessary enabling capability for a federated railway data ecosystem, but it is not sufficient on its own to establish an operational data space. Its effectiveness depends on complementary capabilities for identity, trust, governance, semantic interoperability, contract negotiation and data transfer. The demonstrator also indicates that the value of metadata discovery increases when it is directly integrated into applications and connector-based exchange workflows.

The validation was conducted within the MOTIONAL Living Lab and therefore provides evidence of technical feasibility rather than large-scale operational readiness outside of the project. The number of participants and validated scenarios was limited, and the Metadata Broker was assessed primarily as part of the overall Federated Data Space rather than through an isolated, large-scale evaluation. In addition, some use cases involving real-time or event-driven data were not fully implemented. The results should therefore not be interpreted as evidence of production-scale deployment readiness.

Future work should address the scaling of catalogue federation and participant onboarding, the semantic harmonisation of railway metadata, the validation of discovery mechanisms with larger and more heterogeneous datasets, and the support of more demanding real-time and event-driven scenarios. Further alignment with evolving data space standards and governance frameworks will also be required. These activities can build on the demonstrated architecture and extend the Metadata Broker towards an operational discovery capability for the Federated Rail Data Space.

# 10. References

[1] Eclipse Foundation, Dataspace Protocol Specification, Eclipse Dataspace Protocol, latest applicable version.

[2] Eclipse Foundation, Eclipse Dataspace Components (EDC) – Federated Catalogue, Eclipse Foundation, open-source reference implementation.

[3] International Data Spaces Association (IDSA), International Data Spaces Reference Architecture Model (IDS-RAM) 4.2, International Data Spaces Association, 2024.

[4] Gaia-X European Association for Data and Cloud AISBL, Gaia-X Architecture Document, Gaia-X European Association for Data and Cloud AISBL, latest applicable version.

# ANNEX A: Use Cases

Next to the transfer of data, one of the goals during the development of the rail data space was the implementation of services. This would enable different use-cases ranging from the prediction of track settlements to maintenance decisions.

The first step was to create detailed descriptions of the proposed use cases to later derive the necessary technical requirements for the data-space and app-store. These could range from requiring simple data transfers to handling of streaming or even real-time data transfers. The different requirements introduced different levels of complexity, some of which necessitated additional improvements to the underlying connector technology.

Since the current connector technology in the data space sandbox provided by T-Systems LivingLab was not able to meet all the necessary prerequisites, it was not possible to fully implement all of the use cases. Therefore, the focus for the upcoming Wave 2 and 3 activities is to further explore and develop the rail-specific connector requirements such as those for the real-time data exchange.

This section lists all discussed use cases including their description, the requirements related to the data space, their implementation status and, if available, their interface specification. These use cases are:

- Monitoring of Track Settlement and Identification of Single Faults in Switches
- Maintenance Decision Tool
- Digital Twin of Point Machine
- Track and Positioning regional Lines and Data Yard Automation

## 1. Monitoring of Track Settlement and Identification of Single Faults in Switches

This use case was developed in WP 10 and WP 11 of *FP3 – Iam4Rail* by voestalpine Rail Systems, voestalpine Signalling Austria, and Virtual Vehicle Research. It aims to predict the quality of the switches with regard to track settlement while also identifying single faults. Therefore, measured data from a real switch is continuously fed into the simulation model. The free parameters of the simulation are trained on the provided data – historical and current– to give accurate predictions of future behaviour. The more data that is available, the better the prediction will be. This prediction can then be used to estimate necessary maintenance actions by comparing the prediction with a limit specified by the infrastructure manager. The use case is implemented in the Digital Twin sandbox developed by Virtual Vehicle Research and connected to the data space. As such, it can be executed through the ERJU App Store demonstrator.

Figure 12 provides an overview of the use case. The data space is depicted on the left and acts as the data provider, delivering the inputs required for the use case. Its execution can either be triggered manually by a user or automated to run whenever new data becomes available. The use

case itself is implemented in a Digital Twin sandbox developed and hosted by Virtual Vehicle Research. Within the sandbox, the data is used to train a model that predicts the development of a previously defined quality index. The resulting behaviour of the quality index is then transferred back to the App Store, which acts as the data consumer.

An infrastructure manager (Table 6) can subsequently compare the time dependent development of the quality with a predefined quality threshold. Taking into account the costs and availability of machinery and track access, this information can support decisions regarding necessary maintenance. Such decisions can also be supported by automated tools, as described in the "Maintenance Decision Tool" use case in Section 2 of ANNEX A that uses the output of the "Monitoring of Track Settlement and Identification of Single Faults in Switches" use case as input.

**Table 6. Overview of Roles and Requirements**

| Data Type | Size | Format | Provider | Consumer | Data Transfer |
|---|---|---|---|---|---|
| Vehicle Collective | MB | .json | Train Operator | Research Company | Pulled on demand, updated regularly |
| Track Layout | MB | .json | Infrastructure Manager | Research Company | Pulled on demand, Static data |
| Track Geometry | MB | .json | Infrastructure Manager | Research Company | Pulled on demand, updated regularly |
| Maintenance Actions | MB | .json | Infrastructure Manager | Research Company | Pulled on demand, updated regularly |
| Vehicle Models | MB | .spck | Rolling Stock Operator | Research Company | Pulled on demand, Static data |
| Forecast Window | KB | .json | Asset Manager | Research Company | Pushed manually by user Event-based data |
| Forecast Output | KB | .json | Research Company | Asset Manager | Pushed automatically when results are available, Event-based data |

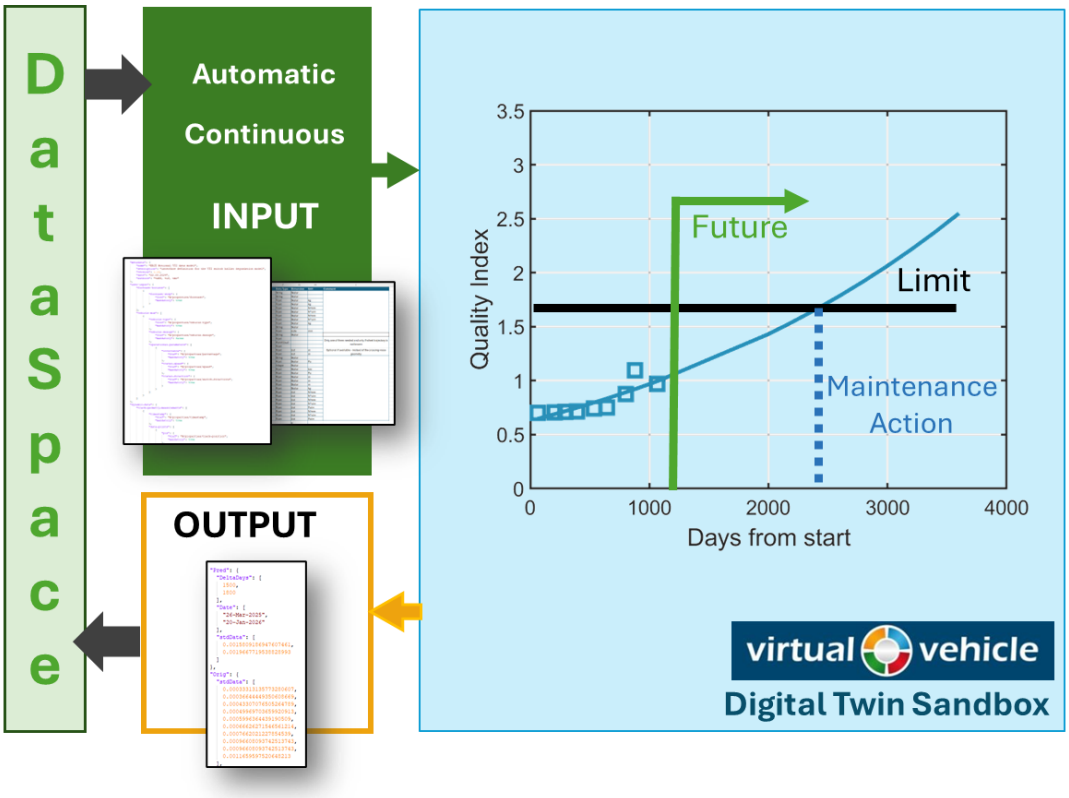



**Figure 12. Overview of the use case "Monitoring of Track Settlement and Identification of Single Faults in Switches"**

## 1.1 Interface description and Data Model

This use case requires data from different sources. The first source is called user data and consists of the forecast horizon, which consists of future dates for which the quality should be predicted, and the vehicle mix that passes through the switch at regular intervals. In most cases, the latter will be automatically generated from existing operational data. However, the acquisition of new vehicles in the near future or changes in operational planning might affect the prediction. By giving the user the option to determine the actual vehicle mix used for the prediction, such changes can be accounted for. An overview of the user inputs is given in Table 7, Table 8, Table 9, Table 10, Table 11 and Table 12.

**Table 7. User Inputs**

| Category | Parameter | Format | Data Type | Dimension | Unit | Comment |
|---|---|---|---|---|---|---|
| Forecast Horizon | Forecast Step | CSV | Float | List | months | |
| Vehicle Mix | Vehicle Type | CSV | Float | List | - | Can always change and is usually determined from the measured vehicle |
| | Vehicle Design | CSV | Float | List | - | |
| | Occurrence | CSV | Float | List | percentage | |
| | Travel Speed | CSV | Float | List | m/s | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Travel Direction | CSV | Float | List | - | collective (see Additional Quantities) |

**Table 8. Dynamic Data**

| Category | Parameter | Format | Data-Type | Dimension | Unit |
|---|---|---|---|---|---|
| Track Geometry | time-stamp | CSV | Datetime | List | - |
| | position | CSV | Float | List | km |
| | longitudinal-level | CSV | Float | List | M |
| Maintenance Actions | time-stamp | CSV | Datetime | List | - |
| | maintenance-type | CSV | String | List | - |

**Table 9. Output**

| Category | Parameter | Format | Data Type | Dimension | Unit | Comment |
|---|---|---|---|---|---|---|
| Forecast Horizon | forecast-step | CSV | Float | List | months | Output values always per sleeper for forecast horizon (see user input) |
| Sleeper | Bending | CSV, Mat | Float | List | m | |
| | compression | CSV, Mat | Float | List | Pa | |
| | force | CSV, Mat | Float | List | N | |
| | settlement | CSV, Mat | Float | List | m | |

**Table 10. Static Data Super-structure**

| | | Data | JSON | Float | List | mm |
|---|---|---|---|---|---|---|
| Switch | | Switch Type | JSON | String | Scalar | - |
| Switch Geometry | | Geometry CAD | STP | Float | | - |
| | | Geometry Scan | STL | Point Coud | | - |
| | | Geometry Calipri | XML, Mat | Float | | - |
| Wheel Trajectory | | Track Position | CSV | Float | List | m |
| | | Vertical Movement | CSV | Float | List | m |
| Rail | | Profile Type | JSON | String | Scalar | - |
| | | Elasticity | JSON | Float | Scalar | Pa |
| Sleeper | Sleeper | Number | JSON | Integer | Scalar | - |
| | | Track Position | JSON | Float | Scalar | km |
| | | Modulus of Elasticity | JSON | Float | Scalar | Pa |
| | | Length | JSON | Float | Scalar | m |
| | | Width | JSON | Float | Scalar | m |
| | | Height | JSON | Float | Scalar | m |
| | | Mass | JSON | Float | Scalar | kg |
| | Sleeper pad | Stiffness | JSON | Float | List | N/mm |
| | | Damping | JSON | Float | List | Ns/m |
| | Ballast | Stiffness | JSON | Float | List | N/mm |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Pad | Damping | JSON | Float | List | Ns/m |
| | | Modulus of subgrade reaction | JSON | Float | List | Pa/m |
| | Ballast | Stiffness | JSON | Float | List | N/mm |
| | | Damping | JSON | Float | List | Ns/m |
| | | Modulus of subgrade reaction | JSON | Float | List | Pa/m |

**Table 11. Static Data Vehicle**

| Component | Parameter | Format | Type | Dimension | Unit |
|---|---|---|---|---|---|
| metadata | vehicle-type | JSON | String | Scalar | - |
| | vehicle-design | JSON | String | Scalar | - |
| carbody | carbody-mass | JSON | Float | Scalar | kg |
| bogie | bogie-mass | JSON | Float | Scalar | kg |
| primary-suspension | stiffness | JSON | Float | Scalar | N/mm |
| | damping | JSON | Float | Scalar | Ns/m |
| Secondary-suspension | stiffness | JSON | Float | Scalar | N/mm |
| | damping | JSON | Float | Scalar | Ns/m |
| wheelset | mass | JSON | Float | Scalar | kg |
| | wheel-profile | JSON | String | Scalar | - |

**Table 12. Additional quantities**

| Value | Parameter | Format | Type | List type | Unit | Comment |
|---|---|---|---|---|---|---|
| Deflection Measure-ments | Time Stamp | CSV | Datetime | List | - | Measurement of the vertical deflection with special measuring trolleys. This enables to determine the system parameters stiffness and damping of the ballast (or overall superstructure). |
| | Distance to Reference | CSV | Float | Sub-List | km | |
| | vertical-deflection | CSV | Float | Sub-List | m | |
| Settle-ment Measure-ments | Time Stamp | CSV | Datetime | List | - | Measurement of the vertical settlement with a stationary measurement at the turnout. They enable to calibrate the system parameters 'travel distance'. |
| | Track Position | CSV | Float | Sub-List | m | |
| | Settlement | CSV | Float | Sub-List | m | |
| Hammer Tests | Time Stamp | CSV | Datetime | List | - | Measurement of the impedance of the rail system. They enable to determine the system parameters stiffness and damping for sleeper soling. |
| | Distance to Reference | CSV | Float | Sub-List | m | |
| | acceleration | CSV | Float | Sub-List | $m/s^2$ | |
| Vehicle | Time Stamp | CSV | Datetime | List | - | If the vehicle mix is not |

| | | | | | | |
|---|---|---|---|---|---|---|
| Collective | Count | CSV | String | List | - | specified by the user |
| | Type | CSV | String | List | - | |
| | Design | CSV | String | List | - | |
| | Axles Count | CSV | Integer | List | - | |
| | Weight | CSV | Float | List | kg | |
| | Travel Speed | CSV | Float | List | m/s | |
| | Travel Direction | CSV | Float | List | m/s | |

## 1.2 Implementation Status

A demo version of this use case was fully implemented within the FP1 MOTIONAL Federated Data Space demonstrator. This demo version was simplified in terms of functionality, as the main goal was the development of the underlying framework technology and IT infrastructure. The use case was presented live during the demonstration event and formed part of the validation.

# 2. Maintenance Decision Tool

The use case “Maintenance Decision Tool” was realized using the zentrak platform, a digital asset and maintenance management solution that supports infrastructure managers in making data-driven maintenance and investment decisions throughout the complete lifecycle of railway assets. The tool combines asset information, maintenance records, condition monitoring data, and analytical results from external applications to provide a comprehensive decision-support environment. It is implemented as the asset management endpoint of the MOTIONAL Data Space demonstrator and serves as the consumer of prediction results generated by external Digital Twin and analytics services.

Within the implemented MOTIONAL use case, the Maintenance Decision Tool receives prediction results generated by the "Monitoring of Track Settlement and Identification of SingleFaults in Switches" application through the tmOS Marketplace. The transferred results are linked to the corresponding turnout and become part of the digital asset record. This allows maintenance engineers and asset managers to combine historical asset data, current condition information, and predicted future asset behaviour within a single software environment.

The Asset Management functionality provides a standardized asset and component register, lifecycle tracking, installation history, localization information, digital product passports, and asset health indicators. The Maintenance Management functionality enables maintenance planning, inspection management, checklist-based execution, work order management, condition monitoring integration and trend analysis. Through these capabilities, maintenance strategies can evolve from corrective and preventive approaches towards condition-based and predictive maintenance.

A key element of the solution is the Digital Asset File concept. Each asset can be uniquely identified through a Digital Touch Point based on GS1-compliant Data Matrix Codes. By scanning the code,

users obtain direct access to asset-related master data, technical documentation, maintenance guidelines, inspection records, warranty information, and lifecycle data. This allows maintenance personnel to access all relevant information directly in the field via mobile devices.

The Maintenance Decision Tool platform is designed for interoperability and can exchange data with external systems through standardized interfaces. Within the MOTIONAL demonstrator, turnout master data is synchronized with the tmOS Marketplace, while prediction results generated by external Digital Twin services are transferred back into the Maintenance Decision Tool for further analysis and maintenance planning. This demonstrates how a federated data space can connect data providers, analytics services, and asset management systems while maintaining data sovereignty and secure data exchange according to IDSA principles. An overview of the roles and requirements is given in Table 13.

**Table 13. Overview of Roles and Requirements**

| Data Type | Size | Format | Provider | Consumer | Data Transfer |
|---|---|---|---|---|---|
| Turnout Master Data | KB | JSON | Asset Manager | Research Company | Pulled periodically, updated on demand |
| Maintenance Records | KB-MB | JSON | Asset Manager | Maintenance Manager | Updated regularly |
| Condition Monitoring Data | MB | JSON | Monitoring Systems | Asset Manager | Pulled periodically |
| Prediction Results | KB | JSON | Research Company | Asset Manager | Pushed automatically when available |
| Maintenance Recommendations | KB | JSON | Asset Manager | Maintenance Manager | Generated on demand |

## 2.1 Implementation Status

The integration between the tmOS Marketplace and zentrak has been implemented and demonstrated within the MOTIONAL Federated Data Space demonstrator. Turnout master data can be synchronized from zentrak to tmOS, and prediction results generated by external analytics services can be transferred back into zentrak and associated with the corresponding asset. The complete workflow from data acquisition through the federated data space, algorithm execution, and maintenance decision support has been successfully demonstrated during the validation activities of WP31.

# 3. Digital Twin of Point Machine

This use case demonstrates how a Digital Twin of a railway point machine (LH 826) (Figure 13) can be exposed as an interoperable data asset through a Federated Data Space, enabling secure and standardised data exchange between infrastructure managers, asset management systems, certification bodies and other authorised stakeholders. The data described here originates from FP1 WP29. Diagnostic data, health scores, simulation outputs and FMU-based evidence generated

by the Digital Twin are made available through provider endpoints and consumed on demand by authorised participants using standardised interfaces.

Hitachi Rail Deutschland can act as the DATA PROVIDER, retaining full control over the data at source, while the Data Space holds only metadata, catalogue entries, access and usage policies, and contract templates. The Data Space itself does not store the actual data; all exchange occurs directly between connectors. This ensures that data sovereignty is fully maintained – no central copy exists and access is strictly governed through negotiated contracts and enforced usage policies.

The use case is closely aligned with FP1 MOTIONAL activities on point machine monitoring and predictive maintenance, where the Digital Twin of the LH 826 point machine is implemented as an FMU-based simulator. The simulator replicates the physical behaviour of the switch mechanism and publishes the following data assets through the Federated Rail Data Space:

- Point machine FMU diagnostic events (MDM format)
- Health score and Residual Useful Life (RUL)
- Operational state: Normal / Degraded / Fault
- Real-time data: current, force, stroke duration
- Simulation scenarios including fault injection
- Development and validation of the LH 826 Point Machine Digital Twin simulator is based on FMU technology.
- Publication of simulation outputs, health scores and FMU-based certification evidence through standardised provider endpoints using data space.

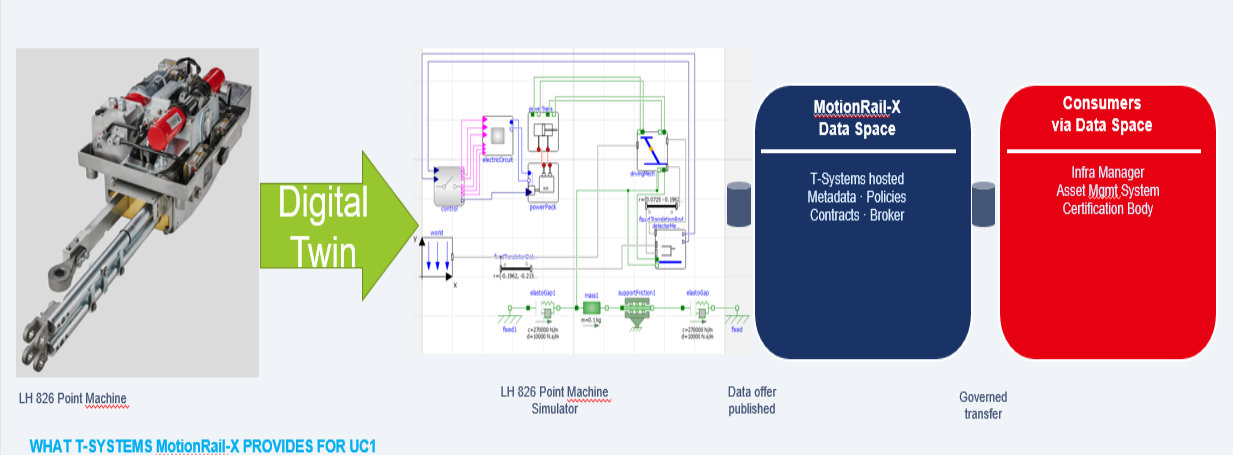



**Figure 13. Overview of the use case: "Digital Twin of Point Machine"**

## 3.1 Implementation Status

While the roles and requirements were specified for this use case as given in Table 14, a full implementation of the use case within the data space was not realized and will be the focus of Wave 2.

**Table 14. Overview of Roles and Requirements**

| Data Type | Size | Format | Provider | Consumer(s) | Data Transfer |
|---|---|---|---|---|---|
| Track Topology | MB | JSON | Railway Infrastructure Manager | Railway Operations Manager/Signalling Supplier | Pulled **on demand** or on update events; pushed manually or automatically when topology changes (e.g., quarterly). |
| Data Sensor | MB | JSON | Railway Infrastructure Manager/Technology Supplier | Maintenance Technician/ Technology Supplier/Signalling Supplier | Pushed in **real-time**, event-driven; transmitted when a train passes |
| Train Data | MB | JSON | Train Operator | Railway Infrastructure Manager/Signalling Supplier | Pushed in **real-time**, generated and transmitted when train passes that specific track section. |
| Track Maintenance Data | MB | JSON | Maintenance Company (i.e. Mermec, Hitachi) | Maintenance Technician/ Signalling Supplier | Pulled **on demand**; updated manually or through maintenance systems when activities are logged. |
| Weather Data | MB | JSON | External Weather service provider | Railway Operations Manager/Signalling Supplier | Pulled **on demand** from external/local weather service APIs or systems. |

# 4. Track and Positioning regional Lines and Data Yard Automation

This use case demonstrates how train positioning and operational context information can be exposed as interoperable data services through a Federated Data Space, enabling secure and standardized data exchange between infrastructure managers, railway operators, service providers and other stakeholders. Positioning information acquired on board the train, together with contextual data describing the operational environment, are made available through provider endpoints and consumed on demand by authorized participants using standardized interfaces.

The proposed approach replaces bespoke point-to-point integrations with a scalable data-sharing architecture, allowing a single implementation to support multiple applications while remaining independent of the underlying communication technology. Connectivity therefore is transparent to the data services and can rely on terrestrial (4G/5G) or satellite communications according to operational availability.

The use case is closely aligned with FP6 activities on train positioning and train-to-cloud communications, where the on-board system acquires GNSS-based positioning data, processed

through a Precision Navigation Module (PNM), and publishes both live vehicle position and contextual information through the Federated Data Space. This integration demonstrates how positioning evolves from a standalone function into a reusable digital asset capable of supporting multiple operational services, particularly in regional and non-interoperable railway environments.

The implementation has been progressively validated through laboratory integration and end-to-end demonstrations, including:

- Integration of the on-board application with GNSS/PNM positioning equipment for live train/vehicle positioning acquisition.
- Publication of live positioning and train context data through standardized provider endpoints.
- Successful interoperability testing with the FDS using provider and consumer connectors.
- Validation of on-demand data retrieval mechanisms for positioning, contextual information, and track geometry data.
- Integration of communication technologies with transparent support for both terrestrial and satellite connectivity.
- End-to-end validation of train-to-cloud data exchange, from the on-board system to authorized data consumers.

Figure 14 illustrates the overall architecture adopted for the use case. The on-board application acquires live train positioning and contextual information, which are exposed through FDS provider connectors. Data exchange is independent of the communications technology and can transparently rely on terrestrial (4G/5G) or satellite connectivity, enabling authorized consumers and services to access the information through standardized interfaces.

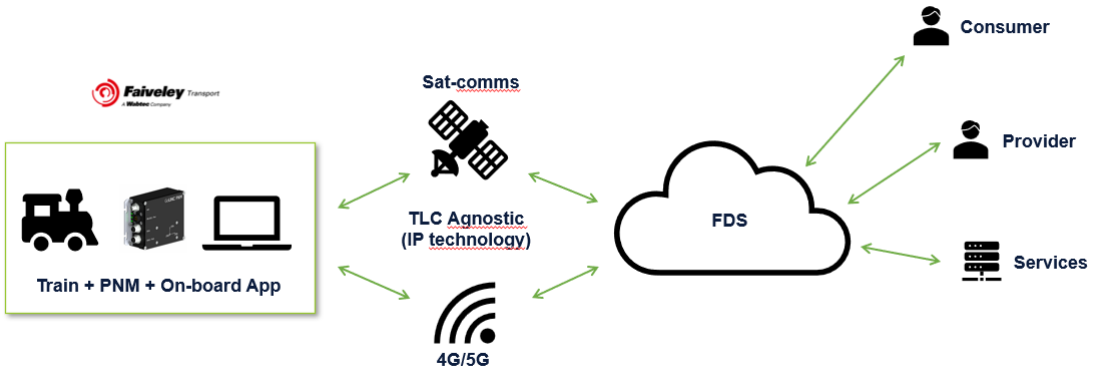



**Figure 14. High-level architecture of "Track and Positioning regional Lines and Data Yard Automation" use case**

## 4.1 Implementation Status

The implementation has been progressively validated through laboratory integration and end-to-end demonstrations, including:

- Integration of the on-board application with GNSS/PNM positioning equipment for live train/vehicle positioning acquisition.
- Publication of live positioning and train context data through standardized provider endpoints.
- Successful interoperability testing with the FDS using provider and consumer connectors.
- Validation of on-demand data retrieval mechanisms for positioning, contextual information, and track geometry data.
- Integration of communication technologies with transparent support for both terrestrial and satellite connectivity.
- End-to-end validation of train-to-cloud data exchange, from the on-board system to authorized data consumers.

The roles and requirements were specified for this use case as given in Table 15.

The use case successfully demonstrated the technical interaction between the Federated Data Space framework and the on-board positioning capabilities developed within EU-RAIL's FutuRe FP6 project, validating the feasibility of exposing interoperable train positioning and contextual data services. However, the activities within FP1 were primarily focused on establishing and validating this demonstrative integration, rather than delivering a fully operational and mature data-sharing service.

As this use case is not planned to continue within the FA1 Wave 2 activities, its further evolution from the Federated Data Space perspective falls outside the scope of this project. Nevertheless, the results achieved provide a solid foundation for future developments, and the demonstrated interaction can be further extended within EU-RAIL FA6 FutuRe Wave 2 activities, particularly in the context of G2 regional railway lines.

**Table 15. Overview of Roles and Requirements**

| Data Type | Size | Format | Provider | Consumer | Data Transfer |
|---|---|---|---|---|---|
| Vehicle Position Records | kB | JSON | Railway Rolling Stock Operator | Regional Train Control<br><br>Signaling System Integrator | Real-time dynamic data, pulled on demand or periodically by Yard/Regional systems; event driven. |
| Vehicle Context Records | kB | JSON | Railway Rolling Stock Operator | Regional Train Control<br><br>Signaling System Integrator | Real-time dynamic data, pulled on demand or periodically by Yard/Regional systems; event driven. |

| | | | | | |
|---|---|---|---|---|---|
| Yard Track Topology | kB | JSON | Yard Manager<br><br>Railway Infrastructure Manager | Regional Train Control<br><br>Signaling System Integrator | Static data, pulled on demand or on update events; pushed manually or automatically when layout changes. |
| Regional Track Line Topology | MB | JSON | Railway Infrastructure Manager | Regional Train control<br><br>Signaling system integrator<br><br>Railway Rolling Stock Manager | Static data, pulled on demand or on update events; pushed manually or automatically when layout changes. |

# ANNEX B: Interaction with other Flagship Projects

This section describes the interactions between FP1-MOTIONAL WP31 and the other Europe's Rail Flagship Projects (FPs), with a focus on knowledge exchange, sharing of experience on data-space technologies and identification of potential cross-fertilisation opportunities.

The main interactions concern FP3 (IAM4RAIL) and FP6 (FutuRe), which are the FPs whose scope shows the strongest thematic alignment with the Rail Data Space activities carried out in WP31 and whose use cases have been mapped in D26.2. Lighter, more general interactions with FP2, FP4, FP5 and FA7/System Pillar are summarised at the end of the section.

In the case of sensitive documents, only this section will be shared with other FPs.

## 5. Interaction with FP3 – IAM4RAIL (Integrated Asset Management for Rail)

One of the main interactions with FP3 was the exchange of knowledge and experience on how a federated data-space approach can support asset-management processes, and to the identification of common ground for future cross-fertilisation.

Sharing experience on data space technologies: the FP1 WP31 team shared with FP3 the lessons learned on the adoption of the IDSA reference architecture, the role of the Metadata Broker as a discovery layer and on the governance implications of a federated approach, so that FP3 could take these elements into account when defining its own asset-management data flows.

In addition, the use cases relevant to the Federated Rail Data Space were collected in D26.2 and linked to FP3 (in particular the “Rail Infrastructure Data Federation” and “Monitoring of Track Settlement and Identification of Single-Faults in Switches” from WP 10 and WP11) are used as a reference to discuss with FP3 how a federated data space could, in the future, support similar asset-management scenarios.

# 6. Interaction with FP5

The interaction with FP5 focused on knowledge exchange with CEIT in Spain and on the planned onboarding of additional participants to the Living Lab. The activity was intended to broaden the range of organisations able to participate in the Federated Rail Data Space and to support the use of additional cross-Flagship use cases. In parallel, the exchange provided an opportunity to share experience regarding data space and connector technologies and thereby support technology acceptance beyond the immediate WP31 consortium context.

From the perspective of WP31, this interaction primarily addressed the organisational and integration requirements associated with extending a federated data space to additional participants. The planned onboarding demonstrated that the applicability of connector technologies depends not only on their technical capabilities, but also on the availability of suitable onboarding procedures and the ability of new participants to integrate their systems and organisational processes with the existing federation. This observation is consistent with the findings from the WP31 implementation and validation activities, which identified organisational onboarding and ecosystem integration as important prerequisites for the further deployment of Federated Rail Data Spaces.

# 7. Interaction with FP6 – FutuRe (Innovative rail services for regional and capillary lines)

The interaction with FP6 focused on extending the discussion on the Rail Data Space to regional and multimodal contexts and on identifying opportunities for reciprocal contamination between the two FPs.

Knowledge exchange regarding regional use cases: the FDS-relevant use case collected in D26.2 and linked to FP6 (Track and Positioning Regional Lines & Data Yard Automation) is used to discuss with FP6 how the concepts developed in WP31 could be relevant for regional-line services and yard automation contexts: FP6's WP9 Task 9.10 demonstrator ("G2 Regional Lines of Train-to-Cloud Communications") offered an early practical use case for validating Federated Data Space connectivity outside a purely synthetic test environment. The demonstrator transmits train data – including GNSS-based positioning, integrated as part of WP10 Subtask 10.3.1 ("Individual demonstrators for cost-effective fail-safe highly accurate train positioning on G2 lines") – from an on-board unit over commercial radio bearers (satellite as primary, cellular as fallback) to a cloud-side sandbox.

For the data-space leg of this chain, an EDC connector was provided by FSTechnology, allowing incoming train position data to be consumed and visualized (via a webapp developed by FT, with an integrated OpenStreetMap/Leaflet interface) following successful retrieval from the sandbox. Test traffic was routed to the T-Systems Data Intelligence Hub LivingLab / FDS sandbox using a lightweight tunnelling setup suitable for this demonstration stage.

While still limited to a sandbox-scale integration rather than a production data space, the exercise confirmed that a G2-line train-to-cloud pipeline can hand off positioning and status data to an IDSA-compliant connector with no bespoke integration effort beyond the connector itself,

providing a useful data point for WP31's broader interoperability goals.

## ANNEX C: Validation Questionnaire

Based on the demonstrator, a Validation Event was held on 7. May 2026. There, the goal was to demonstrate TRL 6 "Technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)". According to BRIDGE2HE H2020-101005071[3], this means that "the prototype has to be demonstrated in a real environment, so as to confirm that the engineering is feasible". In the case of a software, it has to be a "Beta version of the software functionalities tested by selected end-user under a control mode".

To test the functionalities, four validators were invited to test the data space. They were given access to the app store with 2 implemented use cases: the "Monitoring of Settlement and Identification of Single Faults in switches" and the "Maintenance Decision Tool" use case, along with an on-boarding session consisting of a presentation and a Q&A session. Then they were given a deadline of two weeks to test the capabilities. They were able to successfully use the demonstrator, proofing TRL 6. Afterwards they were asked to fill out a questionnaire. Two of the detailed responses received can be found in Table 16, Table 17, Table 18, Table 19, Table 20, Table 21, Table 22 and Table 23.

**Table 16. Participant Profiles**

| Question | Participant 1 | Participant 2 |
|---|---|---|
| Organisation Type | Infrastructure Manager | Research or University |
| Your Role & Data Focus | R&D | Technical |

**Table 17. Strategic Relevance & Expected Impact**

| Question | Participant 1 | Participant 2 |
|---|---|---|
| How relevant is the proposed Data Space to your organization | Moderately relevant | Moderately relevant |
| Which key business areas does it address? | • Maintenance & Reliability (e.g. predictive maintenance)<br>• Data Integration & Interoperability (e.g. reducing fragmentation) | • Data Integration & Interoperability (e.g., reducing fragmentation) |
| What is your expected major impact of Rail Data Space | Cost reduction | Cross-border harmonization |
| What is the single most valuable expected benefit? | Easy access to data and services | Secure interoperability between systems |

[3] BRIDGING THE GAP BETWEEN HORIZONS THROUGH TRANSNATIONAL COOPERATION OF ITS NCP SUPPORT STRUCTURES | Bridge2HE | Project | Fact Sheet | H2020 | CORDIS | European Commission

**Table 18. Priority Use Cases for the Rail Data Space**

| Question | Participant 1 | Participant 2 |
|---|---|---|
| List your Top 3 use cases | • Bring together data & services/Algorithms from different partners à maintenance, Simulations | • improvements in safety and multimodal operating times<br>• Digital twin developments of co-simulations<br>• Decision support applications |
| Timeframe for adoption | More than 3 years | Less than 1 year |
| Primary adoption barrier | Financial (ROI/Cost) | Compliance (Legal/Gov) |

**Table 19. Technical Validation**

| Question | Participant 1 | Participant 2 |
|---|---|---|
| Which data would you share if provided with granular access controls? | To be discussed internally | Operational Data |
| What sovereignty guarantees are strictly required for you to share data? | • Strict Purpose Limitation (Cannot be used competitively)<br>• Full Auditability & Ability to Revoke Access | • Strict Purpose Limitation (Cannot be used competitively)<br>• Guaranteed Anonymization / IP Protection<br>• Full Auditability & Ability to Revoke Access |
| Which standards are essential for interoperability? | - | • TSI<br>• ISO/CEN/CENELEC<br>• Asset Administration Shell (AAS)<br>• IDS / Gaia-X |
| Which best describes your primary capability for external data integration today? | Level 2 (Transitional): Automated but point-to-point (e.g. custom APIs, SFTP file drops) | Level 4 (Advanced): Already utilizing decentralized data space connectors (e.g., Eclipse Dataspace Components) |

**Table 20. Governance & Trust Framework**

| Question | Participant 1 | Participant 2 |
|---|---|---|
| What is critical to build trust in the Data Space? | • Data sovereignty guarantees<br>• Clear liability framework<br>• Auditability | • Data sovereignty guarantees<br>• Transparent access rules<br>• Certification mechanism<br>• Auditability |
| Would you participate in the | No | No |

| | | |
|---|---|---|
| creation of a governance board? | | |

**Table 21. Business Model & Sustainability**

| Question | Participant 1 | Participant 2 |
|---|---|---|
| Acceptable business models | - | Pay-per-use / Transaction |
| Required ROI timeframe | - | Strategic/Long-term only |

**Table 22. Risks & Critical Success Factors**

| Question | Participant 1 | Participant 2 |
|---|---|---|
| Biggest implementation risk? | - | A key point is the system's auditability. Failing to provide a seamless implementation could pose a risk to the adoption of these technologies by the railway ecosystem. |
| Biggest adoption barrier? | | Legal issues involved in obtaining identification |
| Critical success factors (rank top 3) | • Regulatory backing<br>• Technical maturity<br>• Clear economic value | • Technical maturity<br>• Industry alignment<br>• Clear economic value |

**Table 23. Final Feedback / overall Validation**

| Question | Participant 1 | Participant 2 |
|---|---|---|
| What should be improved before moving to deployment | - | It would be nice to have the ability to share data directly from the connector |
| What would convince you to actively participate? | - | It would be beneficial to further promote the use of these types of systems<br>among railway operators and infrastructure managers. I don't think they're<br>ready for it yet. |

| | | |
|---|---|---|
| Additional comments or recommendations? | • GUI is now designed for one application; there is a switch to zentrak. If other services exist in the future, the workflows in the GUI have to be updated, e.g. “transfer”-button<br>• What about the legal and financial framework? Is it planned to integrate the processing of payment? For data and use of services? | - |