AI Platform for Integrated Sustainable and Circular Manufacturing

Deliverable

D3.2 Data Space and Digital TwAIns Design - 1st version

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Author(s):	FhG-IOSB, CORE IC, ENG, INTRA, TECNALIA		
Reviewers:	NISSATECH, NOVA		
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Definitions and acronyms

AAS	*Asset Administration Shell*
AI	*Artificial Intelligence*
AM	*Additive Manufacturing*
API	*Application Programming Interface*
CA	*Consortium Agreement*
CI	*Collaborative Intelligence*
CIM	*Content Information Management*
CLI	*Command-Line Interface*
CM	*Circular Manufacturing*
CRUD	*Create Update Delete*
DL	*Deep Learning*
DLCP	*Digital Lifecycle Passport*
DPP	*Digital Product Passport*
DoA	*Description of Action*
DS	*Data Space*
DSS	*Decision Support System*
DT	*Digital Twin*
DTDL	*Digital Twin Definition Language*
EC	*European Commission*
EDC	*Eclipse Dataspace Connector*
ERP	*Enterprise Resource Planning*
ETSI	*European Telecommunications Standards Institute*
EU	*European Union*
FA³ST	*Fraunhofer Advanced Asset Administration Shell Tools*
GA	*Grant Agreement*
GPU	*Graphic Processing Unit*
GUI	*Graphical User Interface*
HTTPS	*Hyper Text Transfer Protocol Secure*
IDS	*International Data Space*
IDTA	*Industrial Digital Twin Association*
IoT	*Internet of Things*
ISG	*Industry Specification Group*
IT	*Information Technology*
KPI	*Key Performance Indicator*
LCA	*Life Cycle Assessment*
ML	*Machine Learning*
NGSI-LD	*Next Generation Service Interface – Linked Data*
NOVAAS	*Nova Asset Administration Shell*
PLM	*Product Lifecycle Management*
RA	*Reference Architecture*
SDK	*Software Development Kit*
SLA	*Service Level Agreement*
TD	*Thing Description*
TRUE	*TRUsted Engineering*
UML	*Unified Modelling Language*
W3C	*World Wide Web Consortium*
WEEE	*Waste Electrical and Electronic Equipment*
WoT	*Web of Things*
WG	*Working Group*
WP	*Work Package*
XAI	*eXplainable Artificial Intelligence*

Disclaimer

Executive Summary

The Circular TwAIn Project will create a novel AI Platform for Circular Manufacturing value chains, resulting in the development of interoperable circular twins and Data Spaces. This document provides the first version for the Data Space and Digital Twin design in order to develop AI-based Digital Twins for resilient and Circular Manufacturing in the scope of the Circular TwAIn Project.

Section 2 investigates the background technologies with the aim of setting a solid foundation for a common understanding. It relies on the architecture proposed in D3.1 and clarifies the role of the generic Data Space building blocks proposed by the OPEN DEI and Simpl projects. Additionally, it introduces different standards for Digital Twins and explains the Asset Administration Shell (AAS) standard compliant Digital Twins, which will be developed in the Project. Finally, the role of AI in a Digital Twin and across the Digital Twins in a Data Space is also discussed.

In Section 3, we present the conceptual architecture for Data Spaces and discuss the role of Digital Twins and circularity in it. We have identified the Data Space building blocks that need to be specialized/enhanced to accommodate Digital Twins as data sources or circularity as a scope. For each identified need for a building block change, we discussed the challenges and proposed what could be done. Finally, we clarified the role of AI in the Data Space building blocks and explained the reasons why some building blocks can be used as they are, without any specialization.

Section 4 deals with the minimal Data Space and explains all the steps required to achieve it. We provided further details on the tools that could be used for Digital Twin (DT) modelling, DT development, and integration with the Data Spaces. We developed and deployed a demonstrator to validate our Data Space for the circularity approach.

Section 5 summarizes the findings and gives an outlook on the technical implementation in the pilots.

1 Introduction

1.1 Scope of the document

Circular Economy requires highly connected participants in a Circular Value Chain. In such a Circular Economy, a Data Space with Digital Twins is a key enabler for interoperability and asset integration. This deliverable is the result of the WP3 task "T3.4 Design Principles for Data Space and Digital Twins development". The goal of this task is to define the design principles for Data Spaces based on Digital Twins to make it easier for developers to create and manage such Data Spaces. As a domain of application, we consider circularity, as this is one of the key topics of this Project.

This deliverable describes the Data Space and the design of the Digital Twin for Circular TwAIn based on the D3.1 deliverable submitted in month 9 of the Project, which refers to the first version of the conceptual framework and reference architecture. We also considered the deliverable D5.1 as it will be used as the starting point for the implementation of AI-enabled Digital Twins for processes, products and personas.

In addition, this deliverable will be used as the basis for the implementation of the Data Spaces in WP4, which will be described in D4.2 and later in D4.5 as the 1st and 2nd versions of the Data Space implementations for materials, products, production, and people. Moreover, this deliverable will be used to refine the requirements in WP2, which will be available in final form in month 24.

This deliverable reports on the achievements from month three until month twelve. The 2nd and final version of this deliverable will be delivered in month 33. It will consider the feedback from WP4 on implementation of the Data Spaces as well as the concrete deployment in pilots in WP6.

1.2 Document Structure

The deliverable is structured as follows:

- Section 1 clarifies the context of the deliverable and presents the goals.
- Section 2 explains the technologies for a common background.
- Section 3 investigates the changes necessary in Data Space design regarding Digital Twins and circularity.
- Section 4 describes the minimal Data Space for circularity based on Digital Twins, explains steps needed to be done and tools used for that.
- Section 5 summarizes the results and defines the next steps.

2 Background

2.1 Data Spaces and building blocks

2.1.1 OPEN DEI Building Blocks

The EU-funded OPEN DEI Project recently released a position paper to define design principles for Data Spaces and their building blocks [1] involving more than 25 organizations. [2] [3] deal with the topic of domain independent Data Space design. In [4] [5] several Data Spaces for different domain specific application are discussed. The OPEN DEI position paper is based on the design approaches and components proposed in the current research, including but not limited to these books and papers. It aligns the terms and definitions of a Data Space from a domain independent perspective.

Namely, it is a "federated data ecosystem within a certain application domain based on shared policies and rules" [1]. For Circular TwAIn, the application domains are Circular Economies. Participants in this Data Space "access data in a secure, transparent, trusted, easy and unified fashion" [1]. By enabling the Data Space participants to exchange data about processes, products and humans in this fashion, Circular TwAIn aims to transform the linear value chains into Circular Value Chains. The access and usage rights are granted by those who are entitled to publish this data [1]. Data Spaces are comprised of building blocks that are divided into technical and governance building blocks. These building blocks enable interoperability, trust, data value creation and governance within the Data Space [1].

Figure 1 shows the OPEN DEI Project definition of building blocks.

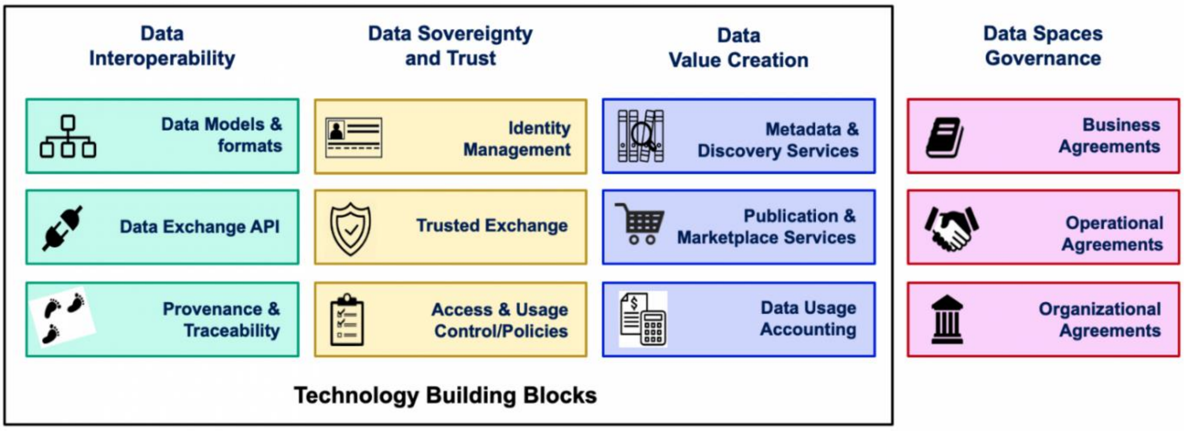

Figure 1: Data Space building blocks by OPEN DEI [1]

The technical building blocks are divided into nine building blocks. Data Spaces can range from a minimal Data Space [6], which only fulfils basic features like secure data transfer, to whole Data Space networks including marketplaces and additional platform services.

Most of these building blocks are designed and implemented in such a way that they are not specific to a certain application domain or use-case. However, the technical building block involving data models and formats is highly specific and needs to be adapted for all participants in the domain, namely the Circular Economy (see section 3.3). Additionally, organizational challenges arise since all stakeholders need to agree on the decentralized architecture and implement it in their infrastructure. The governance building blocks consist of such organizational, business, and operational agreements.

In this context, the International Data Spaces Association (IDSA) offers a reference architecture for Data Spaces named the International Data Spaces (IDS). It provides an information model for describing data assets, a standardized exchange API, and several open-source reference implementations of such building blocks [7], which will be explained in section 3 and 4. For example, components provided by the IDSA are the IDS Metadata Broker [8] for the discovery of data resources in the Data Space. In the remainder of this section, we briefly describe the main functionalities of the verticals used to organize the Data Space building blocks.

Interoperability building blocks

To enable interoperable exchange for participants in a Data Space, standards and specifications for data models & data formats are required. It is necessary to agree on the models that will be used for the data, since the meaning and semantics of the data should be understood by all participants. The formats or models can be chosen freely, but agreeing on the least possible subset of formats and models minimizes the need to convert and map between them.

The next Interoperability building block is the Data Exchange API. For uniform, interoperable data exchange, the participants in a Data Space need to agree on the messages and protocols to be used between company borders. The protocols can be defined freely, but to achieve high interoperability even across Data Space domains, reference architectures like the IDS with its communication patterns should be considered. Additionally, technical implementations [9] to realize this communication are required.

The last building block Provenance & Traceability describes the ability to trace the data path along different Data Space connectors and participants. For this, the connectors usually log data transfers and store them in a central Data Space component available to all participants. This enables traceability of data, even if it has left the connector of the participant.

Data Sovereignty and Trust building blocks

Identity Management in a Data Space is an important building block to create trust and security, so that each participant is really who they claim to be. Especially when exchanging or providing environmental indicators like product and production emissions, trust between participants needs to be established. Each participant in the Data Space requires a unique, verifiable identity which is usually provided by components like an identity provider through identity certificates [7].

In the case of Trusted Exchange, Data Space participants must decide which components are considered trusted and how trust between unknown participants can be achieved. Data Space initiatives like the IDSA usually verify their building block components like connectors and identity providers by 3rd parties to guarantee a high level of security and prevent security flaws during technical implementation [10]. Additionally, an identity is only provided to trustworthy participants.

Access control is concerned with granting and restricting access to data resources [7]. Usage control is an extension to access control that attaches additional obligations to the data usage with usage policies. In Data Spaces, technical enforcement of such access and usage rules would allow to govern the way in which published resources are used by which participants. While access and usage control are important for owners of sensitive data, technical enforcement of the usage rights requires complex systems. In most cases, the usage policies are attached to data resources and the other party is responsible to adhere to these policies.

Data Value Creation building blocks

The Metadata & Discovery Services building block is mostly concerned with enabling participants to find each other and the corresponding data through a protocol. For the metadata, data resources must be described with an information model, for example the IDS Information Model [7]. Otherwise, the Data Space participants will not be able to understand their data descriptions. For the discovery, participants want to query a central component like an IDS Metadata Broker [8] to discover suitable data sources.

The next Publication & Marketplace services building block is concerned with the publication of data offerings and marketplace services enabled by data sharing. The previously mentioned IDS Metadata Broker publishes the metadata of participants in the Data Space. An example for marketplace services in a Circular Economy would be carbon footprint emission trading enabled by offering permits on a marketplace.

Data Usage Accounting describes the monitoring of data usage in the Data Space. For example, providers of battery data can monitor the usage and even charge their customers for the usage of data.

Additional technical building blocks

The OPEN DEI Project also mentions more technical building blocks to facilitate connection of additional systems into the Data Space but because of their edge location do not include them in the shown Figure 1 [1]. Namely, the System Adaptation building block to facilitate the transfer of data to and from participants' systems. The Data Processing building block includes systems connected to the Data Space via systems adapters, which process shared data. The Data Visualisation building block provides data representation and visualisation features for shared data. The OPEN DEI Project states that the list of technical building blocks is not exhaustive and does not dictate a specific technical implementation [1].

Governance building blocks

The Governance building blocks are not technical building blocks, but contain business, operational and organizational agreements between the Data Space participants. Here, the Service Level Agreements (SLA) between companies are defined, which are contracts between a company providing data services and a company using these services. The Data Space participants also need to agree on the functional, technical, operational and legal aspects of the Data Space.

In section 3 we identify building blocks relevant to the circular domain, discuss challenges to their realization with Digital Twins, and describe existing results.

2.1.2 Simpl Design Principles and Building Blocks

Recently European Commission performed a study for specifying the architecture building blocks [11] that would support the creation of an open source, multi-vendor, large-scale, modular and interoperable smart middleware platform which will be the basis for European Cloud Federation enabling the operation and interconnection within and in between various

European Data Spaces and the safe migration of the users to the cloud named Simpl[1]. Since Simpl is intended to become a reference European Open Source Software offering and platform services that will impact the Data Space scene Circular TwAIn, along with Open DEI position paper, has also taken in consideration the work developed by Simpl for the Data Space design principles. Below we provide an overview of these building blocks which can be found in the relevant Architecture Vision Document [11].

Simpl Data Space Design Principles

The Simpl Data Space design specifies ten principles which are [11]:

- **Federation**: The Data Space connects autonomous entities through standards, frameworks, and legal rules. It enables interoperability and information sharing while giving autonomy to service owners. Circular TwAIn should federate data which is a key to enable interoperability and information sharing among the different actors (companies) that will be part of the Data Space. Moreover, in a Circular Economy, multiple federation of different participants/stakeholders should be able to share and exchange data over the circular supply chain.
- **Modularity**: The Data Space component design should be modular, allowing the replacement or addition of components without impacting the rest of the system. Different technologies can be used for each component, tailored to specific purposes. In this way will give the ability to Circular TwAIn to re-use components with different open-source technologies (e.g., Data Space connectors or AI solutions). Moreover, for each pilot Circular TwAIn will be able to deploy specific subset of the system that will map to each scenario.
- **Loose Coupling**: Components and services have minimal dependencies on each other. Standardized APIs ensure that changes to services do not impact consumers. Service owners can switch components or modify data records without affecting end users. Also extending the modularity Loose Coupling will enable Circular TwAIn to use different AI and DT implementations that will facilitate the specific pilot needs.
- **Resilience**: The architecture is fault-tolerant, minimizing the impact of failures in one component on others. Single points of failure are avoided to achieve a distributed architecture.
- **Agnosticism**: Services are technology-agnostic and can be executed in any environment.
- **Composability**: Services can be composed with other services to create new aggregated services. Circular TwAIn should provide the ability to build complex workflows for facilitating the population of Digital Twins and provide lifecycle assessment metrics using the data exchanged thru the Data Space.
- **Interoperability**: The Data Space enables interoperability among participants, facilitating resource sharing in a specified manner and is agnostic to specific implementation details. Circular TwAIn will enable data sharing in an interoperable manner by using compliant Data Space connectors and pre-defined vocabularies

[1] *https://digital-strategy.ec.europa.eu/en/news/simpl-cloud-edge-federations-and-data-spaces-made-simple*

and data models (for materials, products and processes) that should be followed from the Data Space participants.

- **Scalability**: Vertical scaling (adding resources to a single node) and horizontal scaling (duplicating nodes) are possible to meet user demand.
- **Security, Privacy & Trust**: Users interact in a secure and trustworthy environment, compliant with regulations. Data confidentiality, availability, integrity, and privacy are guaranteed.
- **Discoverability**: Services deployed in the Data Space are exposed and discoverable through a service registry or catalogue. Circular TwAIn will provide appropriate catalogues to discover participants and data within the Data Space in an interoperable way.

All the Simpl design principles listed above are aligned with what Circular TwAIn is targeting, which is only restricted, in some cases, by the maturity level it is intending to reach within the duration of the Project.

Simpl Building Blocks

Following the Data Space design and specifications delivered by Simpl, in this section we provide an overview of the layers and the included building blocks that support the Simpl Data Space and are of Circular TwAIn interest. Simpl is structured into four architectural layers the Data Layer, the Infrastructure Layer, the Administration Layer, and the Governance Layer shown in Figure 2 below.

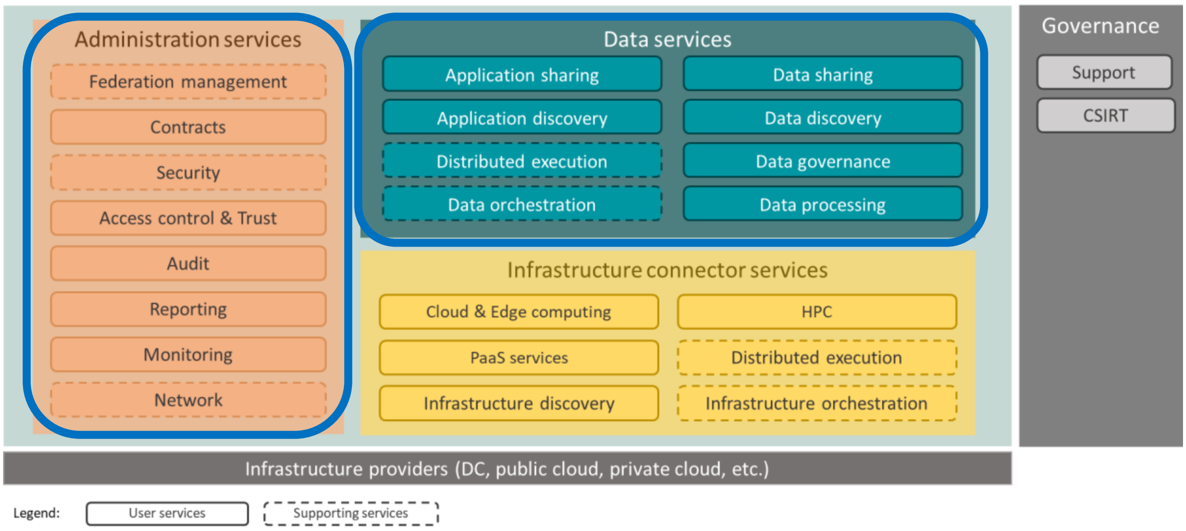

Figure 2: High-level overview of Simpl capabilities and architecture layers [11]

In Circular TwAIn we are mainly interested in the Data and Administration Layers:

- **Data Layer:** This layer facilitates the exchange of data assets and applications. It enables data consumers to access various types of data from different providers, promoting interoperability between providers and consumers. It includes services for sharing, managing, and analysing data and applications.
- **Administration Layer**: Spanning the data and infrastructure layers vertically, the administration layer provides services necessary for the proper functioning of these layers and the entire Data Space. It includes services related to security,

identification, access control, monitoring, and more. The administration layer enables the federation of different actors within Data Spaces and allows actors to operate their components effectively.

The data layer building blocks (shown in Figure 3 below) consists of two prominent capabilities: Application sharing and Data sharing. These capabilities enable the exchange of data and applications between providers and consumers within the Data Space. In Circular TwAIn's pilots we are interested mainly in the Data sharing, so we are not going to further comment the Application sharing. The Data sharing design supports:

- Simple data transfer mechanisms as well as specialized types like bulk transfer and data streaming which is going to be used from Circular TwAIn for exchanging data between actors for supporting Circular Economy scenarios.
- A datastore connector facilitates the connection to the backend data store of the data provider, which can vary from file storage to a relational database system. In Circular TwAIn the datastore will persist the data to the local (participant's) repository for further processing or data sharing.
- Data processing tools are provided to process data close to its source, including data anonymization tools to protect data privacy. Circular TwAIn will be able to use Digital Twin solutions (e.g., AAS) and eXplainable Artificial Intelligence (XAI) environments that will enable the data manipulation and processing.
- Data governance tools enable end users to verify the integrity and quality of the data assets.
- Consumers can discover assets within the Data Space using the Data discovery capabilities. Providers make their data assets discoverable by submitting well-structured metadata descriptions in a standardized format. Consumers can then query catalogues to find suitable assets, which provide information on the content, consumption guidelines, and applicable policies. In Circular TwAIn the data discovery will be facilitated with the vocabularies that will be specified but also the well-defined DT models (e.g., AAS).
- Additional services in the data layer orchestrate data assets across actors in the Data Space. The Data orchestration and Distributed execution capabilities allow actors to pool data from different sources and manage partial sets of data across infrastructure providers when executing distributed applications. These capabilities enable end users to gather data from multiple providers and distribute it across the infrastructure for use in applications. Circular TwAIn will be capable to orchestrate the local (DS participant) data generating specialized workflows for their transformation/processing using its XAI workbench and DS capabilities.

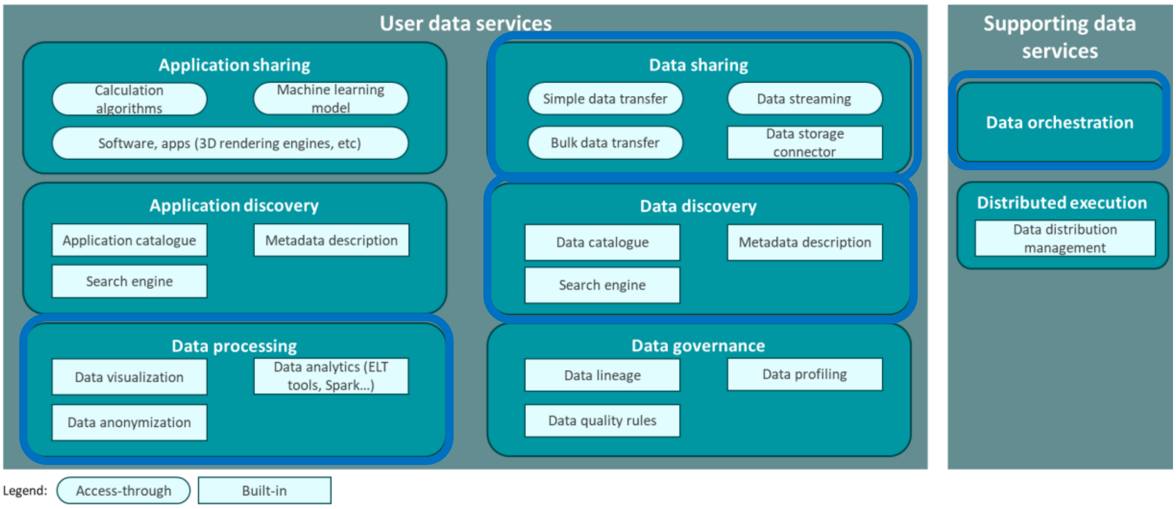

Figure 3: High-level view on the data layer building blocks [11]

The Administration Layer building blocks (shown in Figure 4 below) consists of various building blocks that are responsible for supervision, management, and control functions to ensure the proper delivery of services within the Data Space. These building blocks work together to enhance control and interoperability of the services.

The capabilities within the Administration Layer include:

- Contracts: Determines the correct delivery of licenses, registers billing terms, manages service level agreements, and handles permissions related to data sharing.
- Security: Ensures the agreed level of security encryption and integrity for data transmission and service deployment, providing end-to-end security guarantees.
- Access control & Trust: Manages user roles, authorizations, and attributes for accessing the SMP, including identification, authentication, and authorization services.
- Reporting and Monitoring: Collects real-time information, registers alerts and usage data, and optimizes energy and quality of service. The reporting capability handles historical records and platform usage information.
- Audit: Analyses service delivery against contracts, access, and security requirements by comparing expected performance with actual service delivery. Interacts with reporting and monitoring capabilities.
- Federation management: Orchestrates general administration, supervises services, and manages the connection between Administration Layer components. Ensures federation and interoperability by configuring parameters for SMP components.
- Network: Establishes secure network connections using technologies like virtual private networks and implements firewalls to protect against unauthorized access. Facilitates communication channels for data and application transfers.

Circular TwAIn will focus on some of the core administration functionalities specified by Simpl which are required to fulfil the design principles (e.g., Security, Privacy & Trust) specified above which are the contracts security and access control/trust.

The Administration Layer interacts with the Data Layer. It verifies permissions, contracts, and service level agreements before allowing access to data and infrastructure services. The Administration Layer ensures security, policies, and contracts are adhered to and plays an executive role in addressing any misconduct or abnormal behaviour within the Data Space. Administration Layer is a crucial building block for Circular TwAIn's Data Space and circular design since it will enable the trust between actors.

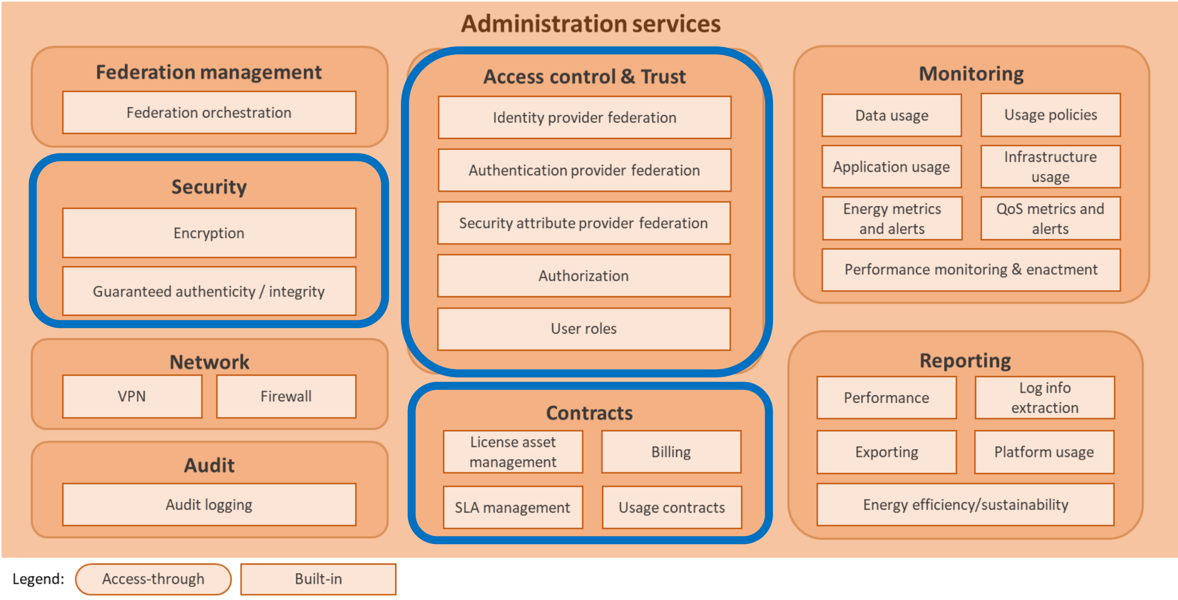

Figure 4: High-level view on the administration layer building blocks [11]

Simpl Architecture Vision Document [11] has taken in consideration and is compliant with Open DEI position paper [1] as far as the design principles and building blocks are concerned especially the ones that are mainly considered for the Circular TwAIn. So, the two design principles are basically compliant with Simpl, in some cases, providing a more fine-grained separation of the building blocks. In Table 1 below an attempt to map the two design principles building blocks can be found based on Open DEI's grouping.

Table 1: Simpl Architecture Vision VS Open DEI position paper Building Blocks mapping

Open DEI position paper	**Simpl Architecture Vision**
Data Interoperability	
Data Models and Formats Data Exchange APIs Data Provenance and Traceability	Metadata Description Data Catalogue Search Engine Data Vocabulary Provider Data Governance • Data Lineage • Data Profiling • Data Quality Rules
Data Sovereignty and Trust	
Identity Management	Identity Provider Federation

<table>
<tr><td>Access and Usage Control/Policies
Trusted Exchange</td><td>Authentication Provider Fed
User Roles
Authorization
Security Attribute Provider Fed
Certification Authority
Encryption
Authenticity and Integrity</td></tr>
<tr><td colspan="2">Data Value Creation</td></tr>
<tr><td>Metadata and Discovery Protocol
Data Usage Accounting
Publication and Marketplace Services</td><td>Federation Orchestration
License Asset Management
SLA Management
Usage Contracts
Billing
Monitoring:
Data Usage
Application Usage
Infrastructure Usage
Usage Policies
Energy Metrics and Alerts
QoS Metrics and Alerts
Performance Monitoring
Reporting
Performance
Platform Usage
Energy Efficiency, Sustainability
Log Info Extraction
Exporting
Audit Logging</td></tr>
<tr><td colspan="2">Technical Building Blocks</td></tr>
<tr><td>System Adaptation
Data Processing
Data Routing and Pre-processing (DR&P)
Data Analytics Engine (DAE)
Data Visualisation
Workflow Management Engine (WME)</td><td>Simpl Data Transfer
Bulk Data Transfer
Data Streaming
Data Store Connector
Distributed Execution Management
Data Orchestrator
Application Management
Data Visualisation</td></tr>
</table>

	Data Analytics Tools Anonymization Data Transformation Calculation Algorithms Software & Apps

2.1.3 DS Dimensions and fields (from D2.2)

In D2.2, an introduction and definition of dimensions and fields of Data Spaces (i.e., business, technologies, data, standards, certificates etc) specifically on Circular Value Chains was presented.

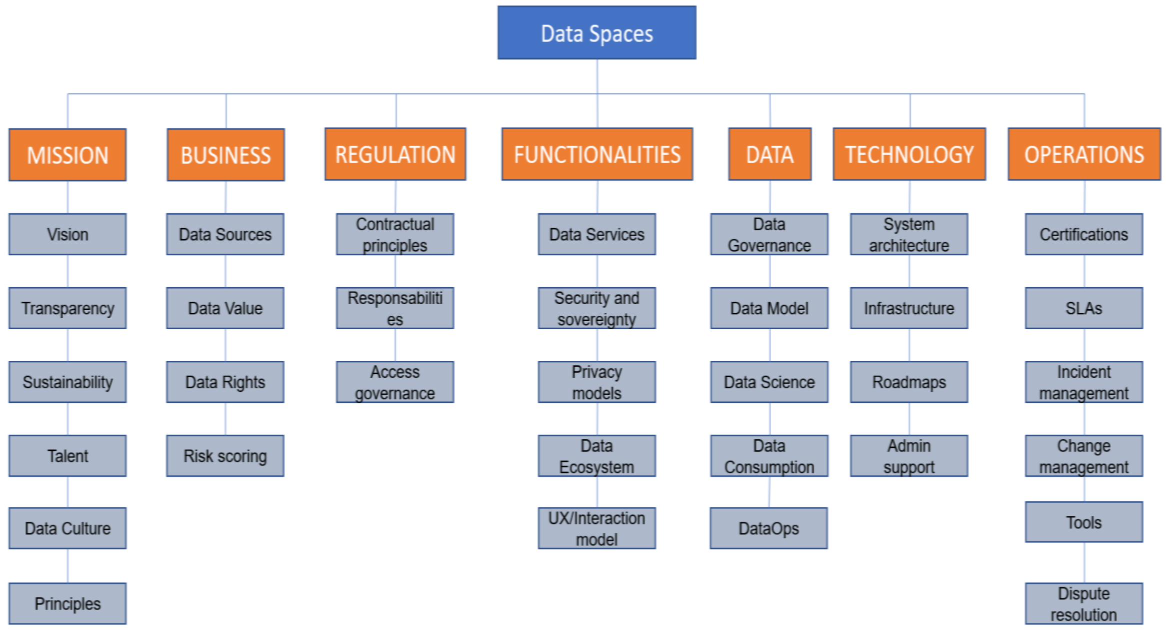

Figure 5: DS dimensions and fields from D2.2

Now, it is part of WP3 to identify and define the aspects that will be addressed in the Project.

Aspects of a DS that are out of the scope of the Project

Data Space's mission:

- Vision: A clear, long-term vision is essential to guide the direction and purpose of a Data Space. This should include a shared understanding of the goals, values, and priorities that drive the organization and its stakeholders.
- Transparency: Transparency is a key principle for a Data Space, as it involves sharing information openly and honestly with stakeholders. This includes being transparent about the data that is collected and used, how it is analysed and shared, and the impact it has on individuals and society as a whole.
- Sustainability: Sustainability involves ensuring that a Data Space's activities and practices are socially, economically, and environmentally responsible. This includes minimizing the negative impact on the environment and ensuring that the benefits of data use are shared equitably across society.

- Talent: Building a talented and diverse team is critical to the success of a Data Space. This includes attracting and retaining top talent with diverse backgrounds and skill sets, as well as providing ongoing training and development opportunities to help staff stay up-to-date with the latest technologies and best practices.
- Data culture: Developing a culture of data literacy and data-driven decision-making is essential for a Data Space. This involves promoting a shared understanding of the value and importance of data, as well as providing training and support to help stakeholders use data effectively in their work.
- Principles: A set of guiding principles or values should underpin the work of a Data Space. This may include ethical principles for data collection, analysis, and use, as well as principles for ensuring data privacy, security, and integrity.

Data Space’s business:

- Data sources: Data sources refer to the various types of data that a Data Space may collect, including both internal and external data sources. This may include structured and unstructured data from a variety of sources, such as sensors, social media, and customer interactions.
- Data value: Data value refers to the potential value that can be derived from the data that a Data Space collects and manages. This includes identifying opportunities to monetize the data, as well as leveraging the data to gain insights and inform decision-making.
- Data rights: Data rights refer to the legal and ethical considerations around the collection, use, and sharing of data. This includes ensuring that data is collected and used in compliance with applicable laws and regulations, as well as protecting the privacy and security of individuals whose data is being collected.
- Risk scoring: Risk scoring involves assessing the potential risks associated with different data sources and data uses. This may include assessing the risk of data breaches or other security threats, as well as evaluating the potential impact on individuals and society as a whole.

Data Space’s regulations:

- Contractual principles: Contractual principles refer to the terms and conditions that govern the relationships between the different parties involved in a Data Space. This includes contracts and agreements between data providers, data users, and other stakeholders, and should cover issues such as data ownership, data use, and data sharing.
- Responsibilities: Responsibilities involve identifying the roles and responsibilities of the different parties involved in a Data Space. This includes data providers, data users, and other stakeholders, and should cover issues such as data governance, data quality, and data security.
- Access governance: Access governance involves establishing policies and procedures for managing access to data within a Data Space. This includes controlling who has access to the data, how the data can be used, and what types of data can be shared with different parties.

Data Space's operations:

- Certifications: Certifications refer to the processes and procedures used to verify that a Data Space is compliant with relevant industry standards and regulations. This includes obtaining certifications for security, privacy, and data governance, as well as certifications for specific industries or use cases.
- Service Level Agreements (SLAs): SLAs are contracts that define the level of service that a Data Space will provide to its users. This includes metrics such as uptime, response times, and data availability, and specifies the consequences if the Data Space fails to meet these requirements.
- Incident management: Incident management refers to the processes and procedures used to respond to and resolve issues or problems within a Data Space. This includes identifying and prioritizing incidents, assigning responsibility for resolution, and tracking progress until the issue is resolved.
- Tools: Tools refer to the software and technology used to manage and monitor a Data Space's operations. This includes tools for monitoring system performance, detecting and responding to security threats, and managing data access and permissions.
- Dispute resolution: Dispute resolution refers to the processes and procedures used to resolve conflicts or disputes between users of a Data Space. This includes establishing clear guidelines for data ownership, access, and usage, as well as establishing a process for resolving disputes that arise between users.

Aspects of a DS that are within the scope of the Project

Data Space's functionalities:

- Data services: Data services refer to the various services that are offered within a Data Space, such as data collection, data storage, data analysis, and data sharing. These services should be designed to meet the needs of stakeholders and should be scalable, flexible, and easy to use.
- Security and sovereignty: Security and sovereignty refer to the measures put in place to ensure that the data within a Data Space is secure and that data rights are protected. This includes implementing data encryption, access control, and data auditing, as well as ensuring that data is stored and managed in compliance with applicable data regulations.
- Privacy models: Privacy models refer to the approaches taken to ensure that individuals' privacy is protected within a Data Space. This includes implementing privacy policies and procedures, such as data anonymization and pseudonymization, as well as providing users with control over their own data.
- Data ecosystem: The data ecosystem refers to the various stakeholders involved in a Data Space, including data providers, data users, and other entities such as regulators and policymakers. A successful data ecosystem requires collaboration and cooperation among these different stakeholders to ensure that data is collected, stored, and managed in a way that is transparent, ethical, and sustainable.

- Interaction model: The interaction model refers to the ways in which stakeholders interact with the data within a Data Space. This includes defining data access and sharing policies, providing tools and interfaces for data analysis and visualization, and ensuring that stakeholders are capable to engage with the data in a way that is intuitive and user-friendly.

Data Space's data:

- Data governance: Data governance involves establishing policies and procedures for managing and using data within a Data Space. This includes defining data ownership, data quality, data security, and data access policies, as well as ensuring compliance with applicable laws and regulations.
- Data model: A data model refers to the structure and organization of the data within a Data Space. This includes defining data elements, relationships between data elements, and data semantics, and should be designed to support the needs of stakeholders.
- Data science: Data science involves using data analytics and machine learning techniques to extract insights and knowledge from the data within a Data Space. This may include data mining, predictive modelling, and statistical analysis, and should be used to inform decision-making and improve business outcomes.
- Data consumption: Data consumption refers to the ways in which stakeholders access and use the data within a Data Space. This may include using data visualization tools, querying data, or using APIs to integrate the data with other applications or systems.
- *DataOps*: *DataOps* refers to the processes and practices used to manage the data within a Data Space. This includes automating data workflows, implementing data quality checks, and ensuring that data is continuously monitored and improved over time.

Data Space's technology:

- System architecture: System architecture refers to the design and structure of the technology systems that support a Data Space. This includes defining the hardware and software components, the data storage and processing systems, the network architecture, and the data security and privacy measures.
- Infrastructure: Infrastructure refers to the physical and virtual resources required to support the technology systems within a Data Space. This includes the hardware, such as servers and storage devices, as well as the software and tools needed to manage and monitor the systems.
- Roadmaps: Roadmaps refer to the plans and strategies for implementing and improving the technology systems within a Data Space over time. This includes identifying new technologies and tools that can be leveraged to enhance the Data Space's capabilities, as well as establishing timelines and budgets for implementing these changes.
- Admin support: Admin support refers to the resources and personnel needed to manage and maintain the technology systems within a Data Space. This includes IT

staff, help desk support, and system administrators, who are responsible for ensuring that the technology systems are running smoothly, resolving any technical issues that arise, and providing training and support to stakeholders as needed.

On the following table (Table 2), we try to relate the different DS building blocks from OPEN DEI, Simpl and D2.2.

Table 2: Different views on Data Spaces

OPEN DEI position paper	**Simpl Architecture Vision**	**D2.2 dimensions and fields**
	Data Interoperability	
Data Models and Formats Data Exchange APIs Data Provenance and Traceability	Metadata Description Data Catalogue Search Engine Data Vocabulary Provider Data Governance • Data Lineage • Data Profiling • Data Quality Rules	Data governance Data model Data science Data consumption *DataOps* Interaction model
	Data Sovereignty and Trust	
Identity Management Access and Usage Control/Policies Trusted Exchange	Identity Provider Federation Authentication Provider Fed User Roles Authorization Security Attribute Provider Fed Certification Authority Encryption Authenticity and Integrity	Security and sovereignty Privacy models Data ecosystem
	Data Value Creation	
Metadata and Discovery Protocol Data Usage Accounting Publication and Marketplace Services	Federation Orchestration License Asset Management SLA Management Usage Contracts Billing Monitoring: • Data Usage • Application Usage • Infrastructure Usage • Usage Policies	Roadmaps Admin support

	• Energy Metrics and Alerts • QoS Metrics and Alerts • Performance Monitoring Reporting • Performance • Platform Usage • Energy Efficiency, Sustainability • Log Info Extraction • Exporting Audit Logging	
	Technical Building Blocks	
System Adaptation Data Processing Data Routing and Pre-processing (DR&P) Data Analytics Engine (DAE) Data Visualisation Workflow Management Engine (WME)	Simple Data Transfer Bulk Data Transfer Data Streaming Data Store Connector Distributed Execution Management Data Orchestrator Application Management Data Visualisation Data Analytics Tools Anonymization Data Transformation Calculation Algorithms Software & Apps	System architecture Infrastructure Data services

2.2 Digital Twins

2.2.1 Introduction to Digital Twins

In recent years the Digital Twins (DTs) technology has gained more and more importance for many domains and applications. The basic concepts of DTs have been developed in the 1990s where dynamical models of real-world components and processes were used for diagnosis of technical systems. The models (ok-models and fault-models) used were linked to sensors in physical systems to monitor the real-world and simulate the future behaviour. In case of discrepancies of real-world and simulated behaviour the kind of discrepancies was used to start a diagnosis of the technical system [12].

Manufacturing use cases have been solved with DTs in the 2000s. An example was the “production assistant” developed for the automotive industry by Fraunhofer IOSB [13]. This DT represented one component of a production control system and was able to signal production problems for the next two shifts of an assembly shop. Therefore, simplified models of manufacturing plants were periodically updated with production data from the real-world factory. The future behaviour of the plant was determined by an event-based simulation.

Although these basic concepts have their origin about 30 years ago, there are many heterogeneous definitions for DTs. The most general definition is given by the Industrial Digital Twin Association (IDTA): “A Digital Twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.”

There are different types of DTs according to [14]: (i) Digital Twin Prototypes, which are built before the physical product exists. They are used for designs, analyses and processes the realize the physical product. (ii) Digital Twin Instances which are linked with the physical counterpart and (iii) Digital Twin Aggregates, which represent data aggregations across multiple instances for the purpose of prognostics and learning.

DTs should support the whole product lifecycle of an asset or product from conception through design and development, to deployment and maintenance and finally to its decomposition. DTs are able to interact using standardize interaction methods. They are accompanied by a standard definition of its term and taxonomy.

The Asset Administration Shell (AAS) is developed by Plattform Industrie 4.0 as part of the Industrie 4.0 reference architecture model. According to the working group 1 (WG1) – “Reference Architectures, Standards and Norms” is an Asset Administration Shell (AAS) a “standardized digital representation of the asset, corner stone of the interoperability between the applications managing the manufacturing systems. It identifies the Administration Shell and the assets represented by it, holds digital models of various aspects (sub-models) and describes technical functionality exposed by the Administration Shell or respective assets.” [15] (Details of the AAS, Part I). The AAS is used to implement DTs for Industrie 4.0. The standardized way ensures interoperability of DTs among different suppliers.

In general, the AAS is a digital representation of an asset. Ideally, it represents all the information and functionalities of an asset. This includes characteristics, properties, parameters, measurement data as well as the capabilities of an asset. An AAS consists of several sub-models describing detailed properties of the asset. The form of these sub-models is standardized through submodel templates. The standardization is organized by the IDTA. Different communication channels can be used to link the AAS to the physical asset it represents.

The AAS standard is described in three specification parts, namely (i) metamodel and serialization of the AAS, (ii) communication/interaction with AAS instances at runtime and (iii) infrastructure for provisioning and connecting. All three parts are under further development.

Besides the AAS standard there are several competing standards which can partly be mapped on each other. The most prominent competing standards are described below:

- The Digital Twins Definition Language (DTDL) was developed for the Azure Platform by Microsoft [16]. The specification of DTDL defines it as “a language, to describe models of IoT plug and play devices, DTs of devices, and logical DTs”.

- The Next Generation Services Interface-Linked Data (NGSI-LD) standard was published by the Context Information Management (CIM) of the European Telecommunications Standards Institute (ETSI) Industry Specification Group (ISG) [17]. It "… enables users to provide, consume, and manage context information in a variety of scenarios and involving multiple actors.
- The Eclipse Foundation developed another standard for DTs called Eclipse Vorto [18]. The main purpose of Eclipse Vorto is to ease the communication of different IoT devices by providing a normalized API for easy integration into software solution.
- The Web of Things (WoT) Thing Description (TD) standard has been published by the WoT Working Group of the World Wide Web Consortium (W3C). The Things Description is described in [19]: "A Things Description describes the metadata and interfaces of a Thing. A Thing is an abstraction of a physical or virtual entity that enables and participates in interactions with the WoT."

According to the Circular TwAIn Description of Action (DoA), the Project will use the AAS standard for the realization of DTs. We note that this is the only standard with a clear link to the industrial domain.

Currently there are several implementations of the AAS. [20] provides a survey and an evaluation of four open-source implementations that are currently to be considered. The following paragraphs are taken from this paper.

The AASX Server [21] is being developed in the context of the IDTA. Its code is based on the AASX Package Explorer which is the most prominent modelling tool for AAS. AASX Server is implemented in C# .NET and comes in three variants: (i) 'core' containing only the server with a command-line interface (CLI) using .NET Core, (ii) 'blazor' also containing a graphical user interface (GUI), and (iii) 'windows' for running on windows without administrator privileges using .NET Framework.

Originating from the BaSys 4.0 and the follow-up BaSys4.2 research projects funded by the German Federal Ministry of Education and Research (BMBF), Eclipse BaSyx [22] provides an implementation of the reactive AAS (Type 2). Eclipse BaSyx provides a feature-rich ecosystem including a client SDK as well as components for asset integration and AAS visualization. It is published under an MIT license and is well-known and often used in the AAS community.

FA³ST Service [23] is being developed at Fraunhofer IOSB as part of the Fraunhofer Advanced Asset Administration Shell Tools for Digital Twins (FA³ST), a collection of tools for modelling, creating and using DTs based on the AAS specification. It is published as open source under Apache 2.0 license. FA³ST Service focuses on AASs on the edge, meaning synchronizing assets and AAS is a central aspect. It also focuses on easy usage for non-expert users while at the same time offering an open architecture that allows for easy extension of functionality.

The NOVA Asset Administration Shell (NOVAAS) [24] is being developed by NOVA School of Science and Technology in the context of the H2020 PROPHESY Project. The implementation follows a no/low-code approach based on Node-RED, a flow-based programming tool, and is published under EUPL v1.2 license. Besides the AAS metamodel and API implementation, NOVAAS offers a web-based graphical user interface that allows the easy creation of dashboards for non-expert users.

The main conclusion of our work reported in [20] that is funded by the Circular TwAIn Project, is that there is no AAS implementation that fully implements the AAS specification. There are some aspects of the AAS specification that are not covered by any implementation, and many that are not fully implemented. However, all considered AAS implementations can support the minimum required functions.

In addition, the paper [20] provides useful feedback to further refine the AAS specification to help software developers understand the semantics of the AAS metamodel and API. Version 3 of the specification was realized in April 2023 and all AAS implementations are expected to implement it. We will repeat the evaluation once implementations have had sufficient time to catch up with the implementation.

2.2.2 Data Twins for Circular Economy

In the context of Circular Economy, the role of Circular Economy flows is paramount in the efficient and sustainable management of resources and materials throughout production processes. The primary objective is to minimize waste and maximize value creation by designing production systems that prioritize the preservation of resources and the continuous reuse of materials. This establishment of a closed-loop system ensures that materials and products circulate in a circular manner, rather than being discarded after use, but entails the proper exchange of information between different stakeholders acting on diverse levels of the value chain. [25]. Indeed, one of the challenges faced by stakeholders is the lack of crucial information. Producers often lack recycling specifications for their products, while customers are often unaware of the environmental impacts associated with the products they purchase, or which EoL strategies can be implemented. To address these issues, innovative concepts such as the Digital Lifecycle Passport (DLCP) and Digital Product Passport (DPP) have been developed at European level. DDP aims to provide a standardized digital representation of a product, containing information about, among which, its design, production, energy and resources consumption. DLCP is built upon DPP concept, covering all the lifecycle phases. These passports facilitate the sharing of comprehensive product information throughout the entire product lifecycle, enabling stakeholders to make informed decisions regarding recycling, reuse, and environmental considerations [26].

To facilitate this seamless sharing of information, the concept of the AAS comes into play. This paves the way for efficient data exchange and utilization across different stages of the asset lifecycle, fostering collaboration, optimization, and informed decision-making [27].

The application of the AAS to circular flows offers several key advantages:

- Each asset is uniquely identified within the AAS environment, accompanied by a comprehensive description that encompasses its properties, capabilities, and relationships. This includes not only physical assets but also digital representations of services or data flows.
- The AAS, when coupled with the DIN 77005-1 standard and other relevant standards, can be extended to include and manage product-related data, as well as lifecycle information (e.g., product design, production, usage, maintenance, repair, and EoL stages) [28].
- The AAS also promotes collaboration and interoperability among stakeholders involved in Circular Economy processes. By providing a standardized framework for

exchanging asset-related information, it enables seamless communication and data sharing among manufacturers, service providers, recyclers, and other participants in the Circular Economy ecosystem.

- Furthermore, the AAS can integrate analytical tools and algorithms to support decision-making processes related to Circular Economy initiatives. For example, it can aid in optimizing asset flow routing, identifying effective end-of-life strategies, or evaluating the environmental impacts and resource savings associated with different approaches.

Within the scope of the Circular TwAIn Project, Data Spaces, in conjunction with the AAS concept, play a fundamental role as the designated storage and retrieval locations for data utilized by Artificial Intelligence (AI) algorithms [29]. These Data Spaces, facilitated by AAS, act as repositories for storing and organizing data, making it easily accessible for utilization by AI systems for analysis, learning, and decision-making purposes. In the specific context of the pilots, the algorithms will leverage these Data Spaces to support circularity initiatives, identifying optimal routes for various end-of-life strategies, such as remanufacturing and de-manufacturing.

2.3 Artificial Intelligence in Circular Economy

2.3.1 Role of Artificial Intelligence in Circular Economy

Artificial Intelligence (AI), when applied to the concept of the Circular Economy, emerges as a transformative tool that can significantly accelerate the transition towards a more sustainable and efficient economic model. The capabilities offered by AI in this context are multifaceted and far-reaching, with potential impacts on various aspects of resource management, waste reduction, and product lifecycle enhancement [30].

AI's ability to process and analyse vast amounts of data in real-time allows for the optimization of resource management. This includes the efficient allocation and utilization of resources, minimizing waste, and maximizing output. AI can identify patterns and trends in resource usage, enabling businesses to make informed decisions about resource allocation, ultimately leading to more sustainable practices. This is particularly relevant in manufacturing industries, where resource optimization can lead to significant cost savings and environmental benefits [31].

Advanced algorithms can forecast waste generation based on various factors, allowing for proactive measures to be taken to minimize waste. Furthermore, AI can optimize waste sorting and recycling processes, increasing the amount of waste that can be recycled and reducing the amount that ends up in landfills. This not only contributes to a cleaner environment but also creates opportunities for the reuse of materials, further promoting the principles of the Circular Economy [32].

AI also has the potential to enhance the lifecycle of products, by monitoring the condition of products in use, predicting when maintenance is needed and preventing premature disposal. At the end of a product's life, AI can help determine the most environmentally friendly and cost-effective disposal method, whether that's recycling, remanufacturing, or discarding [33].

Moreover, AI models in conjunction with DTs – which are virtual replicas of physical systems or processes – can enable advanced simulations, predictions and decision-making. In the context of DTs, whether data-driven (i.e., a DT trained on operational/sensorial data of the system/process), physics-informed (i.e., a DT that is informed on the physical aspects of the system/process), or a hybrid DT (i.e., a combination of data-driven and physics-informed), the AI allows the DT to act in a more dynamic and responsive model that can mimic real-world behaviour more accurately and adapt over time to the physical system/process.

The requirements of AI largely pertain to data quality and quantity, as well as to real-time processing capability. The data should be of high-quality, diverse, and representative that accurately reflect the physical systems in order for the AI models to learn as accurately as possible the behaviour of the physical systems. In most cases DTs model complex systems, therefore AI models need to handle multivariate input data and produce explainable results.

As a final note, the integration of AI models to a DT framework can be executed by training AI models on data (sensorial or otherwise) gathered from the physical system, enabling them to predict future states or detect anomalies.

2.3.2 AI in WEEE and Battery pilots

In the context of the Waste from Electrical and Electronic Equipment (WEEE) and Battery pilots, AI can play a pivotal role in implementing Circular Manufacturing (CM) strategies. AI can facilitate the development of closed-loop supply chains, enabling the remanufacturing or recycling of products (i.e., computers, EV batteries) [34].

The implementation of data-driven DTs can significantly enhance the remanufacturing processes. These DTs, powered by AI, can provide a detailed and accurate representation of the physical products, enabling the prediction of their behaviour, optimize their performance, and identify opportunities for remanufacturing [35]. This can lead to better decision-making in terms of product usage, maintenance, and end-of-life management. In addition, by implementing DT representations of the remanufacturing processes, further insights can be obtained, enabling further optimizations and automations, in the scope of indicating the optimal course of action (remanufacture, recycle or discard used part), as well as providing the end-user with advanced analytics regarding its operation efficiency and cost-effectiveness [36] [37].

2.3.3 AI in Petrochemical pilot

In the case of the Petrochemical pilot, AI can play a crucial role in optimizing the process by reducing CO2 emissions, power and steam consumption. AI's capabilities for analysing vast amounts of data, and modelling the manufacturing process via Hybrid DTs, can provide valuable insights into the plant's operations, enabling the identification of inefficiencies and opportunities for improvement. Moreover, the integration of Hybrid DTs can offer insights regarding the state/condition of the process assets (e.g., reactors, strippers etc.), such as estimated remaining life cycle (i.e., predictive maintenance).

The integration of AI in the Circular Economy offers promising opportunities for sustainable development. From product design and remanufacturing to process optimization, AI can drive innovation and efficiency, making the Circular Economy more achievable and effective. This aligns with our Project's objectives and can significantly contribute to its success [38].

By enabling more efficient use of resources, reducing waste, and facilitating the creation of more sustainable business models, AI can play a crucial role in achieving the goals of the Circular Economy.

3 Data Spaces for Circularity based on Digital Twins

The Circular TwAIn Reference Architecture is based on several specifications and standards and is described in deliverable D3.1 [39]. However, the exact integration and combination of different technologies like DT and Data Spaces components on cloud and edge level along horizontal and vertical transfers is a current research topic. The following sections investigate the changes necessary in Data Space design regarding DTs and circularity.

3.1 Conceptual architecture

Figure 6 shows the Data Space view shared by the International Data Spaces Association (IDSA). It addresses nearly all previously described building blocks except for marketplace services, which are usually built on top existing components.

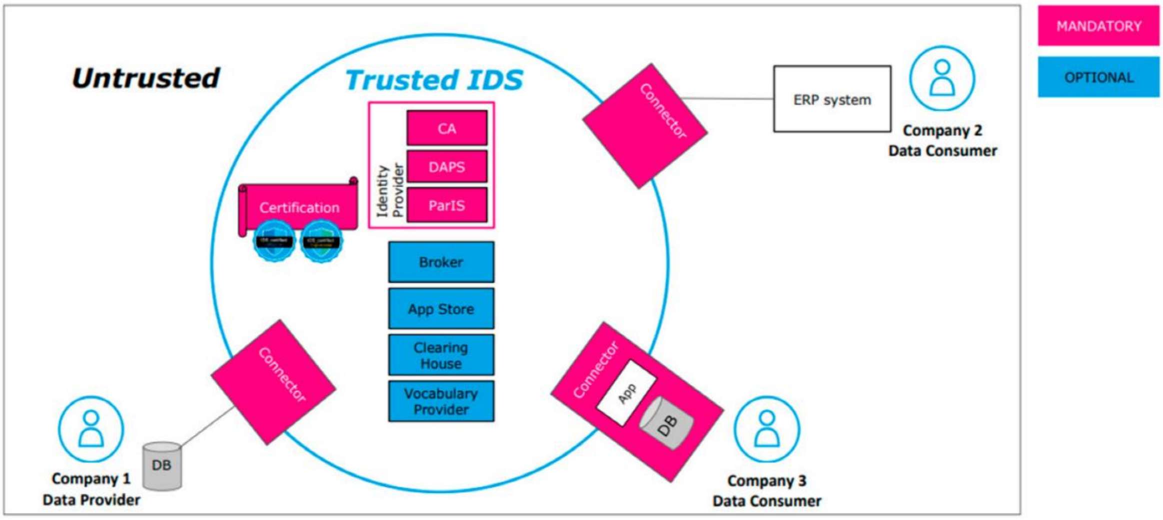

Figure 6: Data Space by IDSA [7]

A central component required for data providers and consumers, is the connector, which is the gateway of an organization to participate in the Data Space. It is part of several technical buildings, see Table 3. Most notably the connector is used to transfer data and conduct data policy negotiations.

The identity provider provides a unique identity for each connector. It is part of the Identity Management building block in the trust building blocks. The connectors store the identity and initiate verification.

A broker is a component where all connectors can register to publish their data offerings to a broader audience. It is also the component used to search for suitable data offerings. This component is part of the data value building blocks, namely it uses the Metadata & Discovery protocol building block and is part of the publication services.

Vocabularies and ontologies are usually provided by a component called the vocabulary provider. Here the semantic meanings can be requested which are used in the descriptions of data offerings. It supports the publication services but is itself part of the data models building block.

The Clearing House logs all data transactions taking place to provide traceability and provenance of data in the network. It also supports the data usage accounting building block to create invoices for data usage.

An App Store is a component to provide additional applications for connectors, e.g., an application to offer emission permits based on the current process carbon footprint. With these applications, additional functionality can be introduced into the connectors if the connector implementation supports installation of IDS Apps.

Table 3 shows an overview over the components and which building block (introduced in section 2.1) they contribute to. The table confirms that all Data Space building blocks could be realized with IDS components.

Table 3: Data Space components mapped to building blocks

IDS components / Data Space technical building blocks	Interoperability	Trust	Data Value
Connector	Provides **Data Exchange API**, stores **Provenance** logs	Enables **Trusted Exchange**	Stores **Metadata** and logs **Data Usage**
Identity Provider		Provides **Identity Management**, enables **Trusted Exchange**	
Broker			Stores **Metadata**, enables **Discovery & Publication**
Vocabulary Provider	Stores **Data Models**		
Clearing House	Enables **Provenance & Traceability**		Enables **Data Usage Accounting**
App Store			Offers additional **services**
Marketplace			Offers additional **services**

3.2 Role of Digital Twins in Data Spaces

This section clarifies how DTs can be "connected" to Data Spaces.

3.2.1 DT-relevant Data Space building blocks

Figure 7 shows the building blocks of the Data Space that need to be considered when releasing a Data Space based on DTs. DTs are part of the Interoperability building blocks, more precisely the Data Models & Formats building block as seen in Figure 3. DTs enable interoperable exchange between participants by defining a subset of suitable data formats and integrating data models. The AAS relies on other domain-specific ontologies and vocabularies but harmonizes the API and integration of data sources into the Data Space. As such, the data formats and models are clear for all participants of the Data Space.

Additionally, they must be considered when describing the metadata and catalogues in the Data Space, otherwise the Data Space participants would not be able to find the correct DT. In general, the goal of the Metadata & Discovery Services building block is to enable Data Space participants to find suitable data sources (DTs).

DTs can also be reflected in marketplace services, e.g., enabling Manufacturing-as-a-service, where capabilities of a machine are offered to all Data Space participants. These services depend on the business case of the Data Space and will be addressed in section 3.3.

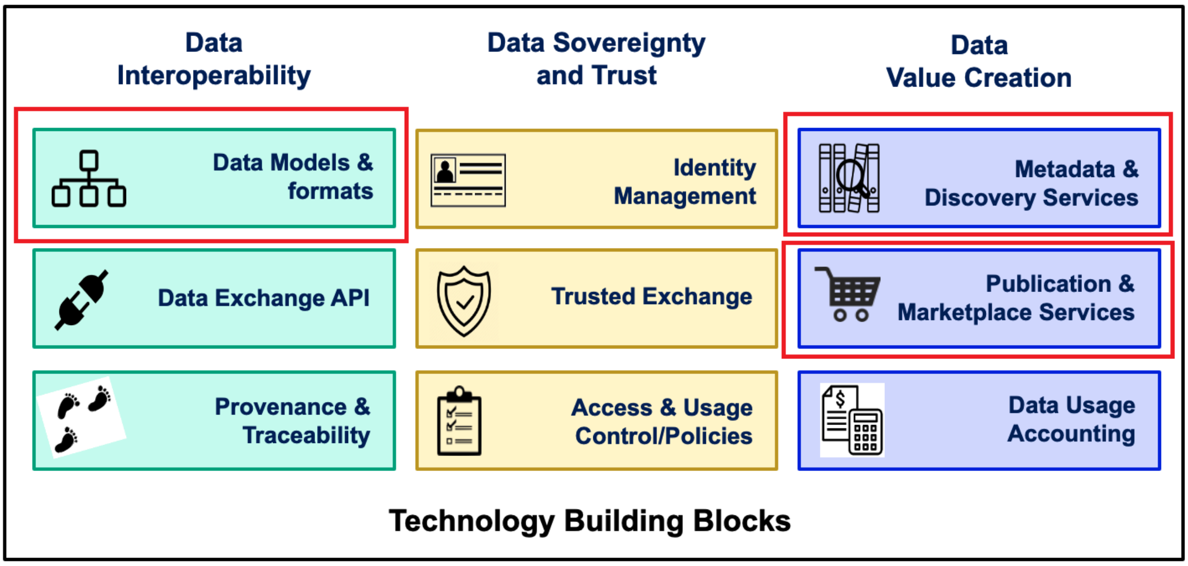

Figure 7: DTs in Data Space building blocks

Other building blocks are not DT-specific since they facilitate Data Space functionality in a generic way. They will be explained in section 3.5.

The remainder of this section discusses the challenges and solutions to realizing the relevant building blocks mentioned above.

3.2.2 DTs & IDS connectors

Circular TwAIn in general proposes DTs for the products, processes, and humans. Additionally, Circular TwAIn proposes usage of the AAS (see section 2.2) as a standard for realising DTs. In the case of the use of an AAS as a data source, it provides a uniform Application Programming Interface (API), a set of defined communication protocols and can itself synchronize several data sources into a logical unit like a Digital Product Passport (DPP). In this case, the DT of a product can provide a DPP, but the two terms are not synonyms since a DT can provide additional functionality like simulation or data-driven services. The ZVEI e.V. proposes the AAS as implementation of a DPP [40].

There are several other specifications to realize standardized DTs [41]. The possibility to reference other ontologies or models in the AAS and the submodel templates, which themselves are models to describe common aspects like a carbon footprint, are advantages in the realization of a DT. We propose the usage of AAS to describe products, processes and humans inside a company while leveraging Data Space building blocks to share the AAS as a data source across company borders. In our view, the AAS is also the most promising solution to realize DPPs but different solutions might emerge as seen in [42].

DTs and IDS connectors can both be deployed inside a company or on cloud infrastructure and used independently. However, DTs usually represent a physical asset found in the company while IDS connectors are gateways to Data Spaces across company borders. As such, we suggest the combination of both concepts as shown simplified in Figure 8: Combination of DT and DS (simplified).

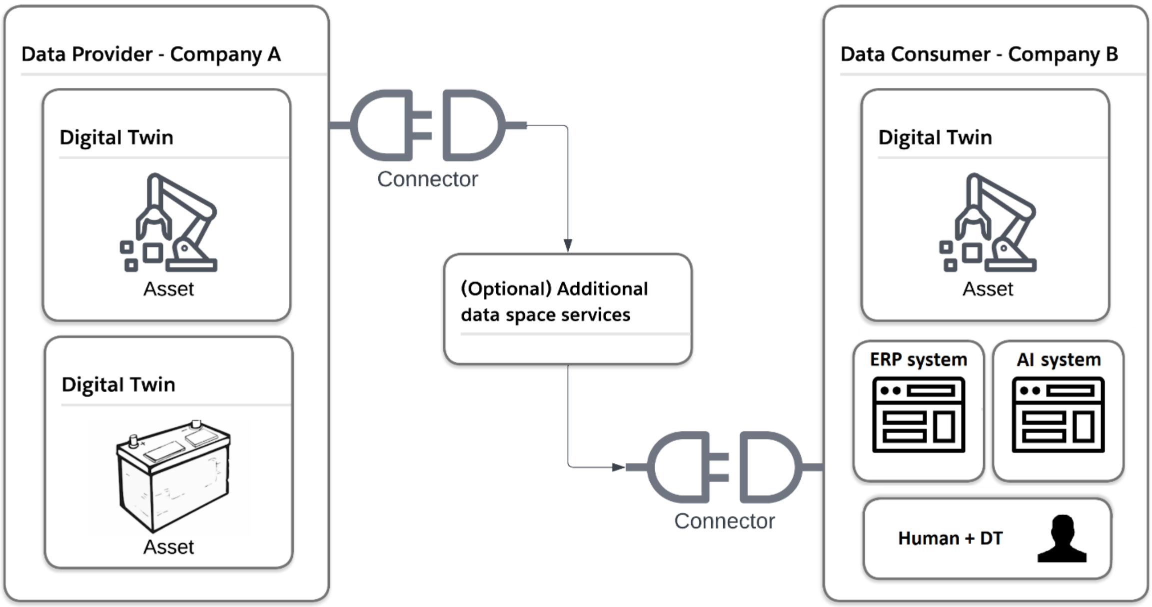

Figure 8: Combination of DT and DS (simplified)

In most cases, IDS connectors initiate data transfers with other IDS connectors over Hyper Text Transfer Protocol Secure (HTTPS) [7]. However, there are also specific Data Space protocols available or in development, like the IDS Communication Protocol (IDSCP) and Dataspace Protocol [9] [43]. In the case of HTTPS, both metadata and payload are exchanged between connectors.

The AAS specification chose two communication protocols (HTTPS, OPC UA) for its API [44], which can be leveraged by IDS connectors for data integration. By describing AAS HTTPS endpoints in the connector metadata, the data will be requested from the AAS over HTTPS (AAS API) and sent to the other participant over HTTPS (IDS API).

If the data source is not a HTTPS endpoint, e.g., an OPC UA machine server or AAS without HTTPS, the connector must support this communication protocol through its backend data services. By using the AAS as a data source in IDS connectors, the integration into the Sata Space is simplified by focusing on the subset of protocols the AAS specified. In this case, the AAS is responsible for the synchronization between AAS and physical asset, process or human.

Regarding the Data Space connectors, Deliverable D3.1 analysed all available connectors and their technology readiness to select suitable solutions. The open-source Eclipse Dataspace Connector (EDC) is a technical implementation for communication between participants in a Data Space with an open community behind it [7]. Different connectors offer specific features, e.g., the open-source TRUsted Engineering (TRUE) Connector [45] supports technical enforcement of usage rules. Connectors can communicate with other connector implementations that implement the same communication pattern.

While other Data Space architectures [7] propose the transfer of data through the connector itself, the Eclipse Foundation proposes a split data and control plane. This means, that after the connector verified the data transfer in the control plane, the data is sent from the data source to the data sink via a split connector data plane. The data transfer is initiated by the connector, which means that the data source needs to support the data plane suggested by the connector. If the connector has a unified control and data plane, the data is transferred directly between the connectors. In this case, the connector requests the data directly from the data source and transfers it to the other connector.

Since the EDC has a split control and data plane while the TRUE connector follows the unified approach in [7] more closely, they are currently not able to communicate. It is a challenge to solve this issue since both connectors have different features and should be interchangeable.

In a Data Space, the connector provides a catalogue of available data sources to other connectors. These data sources can be anything from databases, ERP systems, files, to web services. In all cases, the integration of data sources into the connector or data plane is a technical challenge, which usually requires manual effort. Since there are numerous communication protocols and data formats offered by data sources, we propose the usage of standardized DTs as data sources.

DTs can be deployed on the edge to realize a synchronization between the digital and physical entity in a company. However, they can also be deployed in a centralized cloud to collect public data sources and process data. It is important to note that DTs do not primarily focus on data sovereign sharing. As such the security specification in the AAS is not yet fully specified and a liaison between Platform Industry 4.0 and International Data Spaces Association was formed to solve the issue. In this context, the IDS Industrial Community was formed [46]. We therefore propose to use Data Space connectors across company borders and DTs inside the company [47].

3.2.3 DT registry & IDS broker

In both DT and Data Space domain, there are software components enabling discovery and publication of data sources. In the case of the IDS, an IDS Broker provides a list of IDS connectors with their available data offerings [7]. However, the broker only understands the IDS Information Model and cannot resolve DT requests, like the AAS queries found in the AAS Registry API.

It is vital for participants to register their connector in a broker, since the participants in a Data Space might not know each other before data transfer. Likewise, it is vital to register the DT in a registry so that other DTs can find and interact with each other.

In the AAS specification, a component called AAS registry is used to keep track of all registered AAS instances [15]. Like the IDS Broker, the AAS registry provides a list of available AAS and their submodels.

The Data Exchange API building block also includes registry mechanisms in their specification, e.g., IDS communication includes IDS broker registration. The brokers only store metadata about the data offering, while the data resides inside the company. As an example, brokers like the EDC Federated Catalog or IDS Metadata Broker can be used to store connector descriptions [48] [8].

It is also vital to enable Data Space participants to find specific DT offerings, like a DT describing a certain asset aspect. For this, we propose to include AAS identifiers in the Data Space catalogue description, which in turn allows participants to query the IDS broker for participants offering AAS.

In a previous project [49], we combined the functionality of IDS brokers and AAS registries in a single component. This allowed customers to make use of the AAS API to look for available AAS even if the provider AAS were protected by IDS connectors. This made sense in cross-company scenarios where AAS need to find and interact with each other while not being aware of IDS connectors but leveraging data sovereign data transfers. The task of finding other AAS to communicate with was then handled by the customer AAS or external systems using the AAS API.

However, the data transfers are still required to happen between the connectors so that a valid usage contract can be negotiated. This means that the customer AAS or an external system still needs a connector to handle the data transfer.

The necessity for such a combined broker/registry in Circular TwAIn depends on the pilot requirements, more specifically on whether the customer AAS is tasked with finding the correct data providers. We currently assume that a human operator browses the IDS broker listing AAS data sources, selects and negotiates the data usage and initiates the data transfers to the customer AAS.

3.2.4 DT semantics & IDS vocabulary provider

Semantic meaning in DTs refers to the way the information is structured, communicated, and understood within the DT and the application domain. It involves defining a standardized way to represent and communicate asset-related information. This standardization is crucial for ensuring interoperability between different devices, systems, and services.

In the context of the AAS, there are several concepts to establish syntactic and semantic interoperability. Semantic IDs are used to link a semantic specification to a submodel or submodel element. This specification provides meaning to the element, for example an ontology or a formal specification describing the element in detail [44]. It is possible to define own dictionaries in the AAS that contain semantic definitions of the submodel elements. These semantic definitions are called concept descriptions and are mainly used for attributes and data types in the AAS [50].

While the meta model of the AAS creates a rough syntactic structure, the aspects of an asset can be split across several submodels and elements in any way the company sees fit. Submodel templates define the aspects of the asset to be represented in a specific structure and with specific elements. They are created and standardized by Industry 4.0 working groups allowing for better interoperability between different systems and devices, if companies implement them [51].

In Data Spaces, semantics can also be described in the metadata of the offered data resources. In order to resolve the semantic description, the IDS Vocabulary Provider is a special connector that can be queried for the required semantic description [35]. It can host several vocabularies and ontologies used in annotations and descriptions of data.

In a previous project [49] we tried to leverage this component to add missing semantic IDs in an AAS. Since the IDS Vocabulary Provider hosts several vocabularies and ontologies, it can be queried when an AAS is shared over a connector. For example, an AAS with an element "*tire*" is shared without describing it with a semantic ID. In this case, the IDS Vocabulary Provider can be queried to find a suitable semantic ID based on the context of the AAS. The context might be the asset of the AAS or surrounding elements which are then used to find a suitable vocabulary or ontology. Following the "*tire*" example, the asset might be of type "*railborne vehicle*", allowing to resolve into eClass vocabulary "*28-04-07-07 Wheel tire*". The approach can include simple string or AI supported matching. This matching can happen before the data is offered or during data transit in the Data Space. However, we strongly suggest making use of submodel templates and semantic IDs before the AAS is shared to enable browsing for suitable data resources.

After the semantic IDs are used to reference the ontologies developed in Circular TwAIn, the ontology must be available for all participants to resolve the semantic meaning. This can be done by referencing a URI [52] publicly available or hosted by a Vocabulary Provider.

3.3 Role of circularity in the Data Space building blocks

In this section, the Data Space building blocks are analyzed from the point of view of circularity. The goal is to identify the building blocks that should be extended/adapted to address the circularity aspects. Furthermore, we discuss how the main features of the relevant building blocks could be realized.

Our goal is to realize a Data Space for Circularity and not a Circular Data Space. Even though both terms highlight the integration of data and circularity, they reflect a slight difference in perspective. While the Circular Data Space refers to a Data Space that focuses on managing and leveraging data related to the Circular Economy, the Data Space for Eircularity puts the emphasis on circularity as the primary objective, with the Data Space being the enabling infrastructure.

3.3.1 Circularity-relevant Data Space building blocks

According to [53], five groups of actors are relevant to the activities of forming a circular supply chain: customers, service providers, manufactures, suppliers, third-party recycling companies. Data sharing and collaboration among these various stakeholders can increase the effectiveness of Circular Economy initiatives. The generic Data Space architecture already incorporates mechanisms for secure data sharing and collaboration to enable collective decision-making and innovation. In this section, we focus only on the Data Space building blocks relevant to circularity.

Similar to Figure 7 on Data Space building blocks for DTs, Figure 9 shows the Data Space building blocks that should be extended and adapted to the Circular domain. The relevant building blocks are: (i) data models & formats; (ii) metadata & discovery and (iii) publications

& marketplace. The remainder of this section describes the role of Circularity in each of these building blocks. Section 3.5 explains why the other building blocks are general enough to be applied in any domain and do not require extension for the Circular domain.

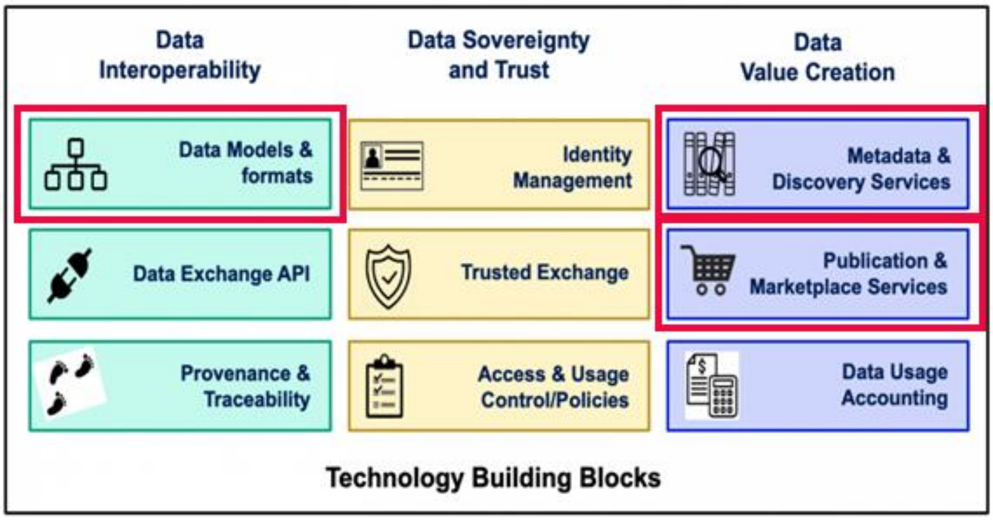

Figure 9: Data Space building blocks relevant for the Circular domain

Data Models & Formats

The Data Space for Circularity should support the collaboration between different partners and thus the integration of various data sources, including data on resource consumption, waste generation, product lifecycle, supply chain information, environmental impact, etc. To enable effective use, the data within the Data Space for circularity needs to be understandable and, if possible, even standardized. This should not only ensure uniform formats for different datasets, but above all a common understanding. For this reason, ontologies would be required.

The goal of a circular ontology would be to facilitate interoperability and data exchange between different systems and stakeholders. By structuring, organizing, and making understandable the complex relationships and knowledge associated with the Circular Economy, the circular ontology would provide a shared understanding of different aspects of the Circular Economy, supporting data integration, interoperability, decision-making, and collaboration.

The challenge here is also to decide which circularity data should be modeled in the circularity ontology and which data should be modeled with AAS submodel templates. In addition, it should be decided whether everything related to circularity should just be semantically linked to the AAS by semanticID even in standardized submodel templates (see section 3.2.4).

Regarding the format, there are several formal representation languages for ontologies such as OWL (Web Ontology Language), RDF (Resource Description Framework), and RDFS (RDF Schema). The choice of the language depends on the requirements in terms of expressiveness and compatibility with existing tools and systems.

Metadata & Discovery

The Metadata & Discovery building block of a Data Space addresses the mechanisms and processes involved in managing metadata and enabling effective discovery of data within the Data Space. Both functionalities are relevant to the Circular Economy, as there are many external data sources that should be considered to enable decisions across the product lifecycle that are in line with a Circular Economy.

Metadata provides descriptive information about the data, and all relevant data for end-to-end processes along Circular Value Chains must be considered. This means that in addition to the data coming via DTs and Digital Product Passports (DPPs), external data sources such as environmental management systems, waste management systems, circular databases (e.g. https://ec.europa.eu/eurostat/web/circular-economy/database, EcoInvent, PSILCA,), etc. should be made available.

On the one hand, there is a need to extend the IDS information model to include the metadata describing these sources. On the other hand, the IDS information model is a generic model that is not limited to a specific domain. It is expected that the IDS information model should be generic enough to allow describing meta-data about external circular systems without extensions. If this is not the case, the proposed solution to this problem is to delegate domain modelling to shared vocabularies and data schemas, such as those provided by the IDS domain-specific communities. More information could be found at: International Data Spaces Information Model (international-data-spaces-association.github.io).

Discovery enables users to find and access the data they need. This would require developing a registry with onboard and search services to ensure the findability and accessibility of DTs, DPPs and external data sources. Depending on the use case, this component can be a central component in the Data Space, like the IDS broker, or it can be local to an organization and then published to the broker.

Publication & Marketplace

The Data Space building block Publication & Marketplace services supports the data providers to publish their datasets and make them discoverable, accessible, and usable for data consumers. Both functions are relevant for the Circular domain.

Since publication services should enable data providers to publish their datasets in a standardized and accessible format, there is a need for such services for all relevant data sources. In the Circular TwAIn Project, the relevant sources for the Data Space for Circularity are the DTs, the DPPs, and the external data sources with circular information. Since the DTs will be AAS-compliant, their data, models, and services will be made available to the Data Space participants via the DT API. The same API can be used for the DPPs if they will be implemented based on the AAS standard as proposed by the Industrie 4.0 platform. How this will be realized depends on the type of a data source (e.g., software systems or databases) and the API available for it. If no API is available, an external data source could be considered an asset and a DT developed for it. In this case, the DT needs to be modelled and the asset connectivity service needs to be implemented. All other required functionality (e.g., synchronization between the Data Space and the external source) will be provided by the DT itself.

As for marketplace services, they should provide value-added services to the Data Space for Circularity by enhancing collaboration and monetization opportunities. This requires not only that each data source is considered separately (e.g., a DPP), but more importantly, that more than one DPP is considered together to provide value chain services. Typical services include: Manufacturing as a service (e.g., who can assemble batteries for me), Recycling as a service (e.g., who can recycle/remanufacture my used batteries), Certification services, Public databases for reference values (carbon footprint), etc. Which services are needed and should be developed depends on the use cases. At this stage of the Project, our pilots have almost no marketplace requirements.

3.3.2 Digital Twins vs. digital product passports

In the Circular TwAIn Project, the DTs will focus on the factory level and the DPPs will be used company wide.

DTs have been used to simulate and optimize the production processes and to model a product or material to analyze its composition and properties and explore scenarios for how it could be transformed or repurposed. The Circular TwAIn Project will extend existing approaches (depending on the use case) by developing AAS-compliant DTs to monitor and optimize processes in real time, and by using data analytics to improve product quality and reduce energy and resource consumption.

On the other hand, DPPs are instruments that provide key information in the terms of climate neutrality and the Circular Economy. They fit into a broader and growing movement aimed at developing business models. However, enabling new business models requires services that allow conclusions and learning effects for the industry, with minimal effort for the creation and management. Since DPPs can play a vital role in scaling and achieving a low-carbon transition, there is a need to develop services to create and manage a DPP as a service. This includes the creation of a DPP metamodel based on the relevant standards, the development of services to instantiate a DPP service based on this metamodel and populating it with data from the DTs resulting in an authenticated, time-stamped dataset that can no longer be modified.

For DPPs, we will follow the DPP4.0 initiative[2], which proposes to use the AAS standard to document and make available relevant product information. The idea is to combine two standards: (i) the ID link for accessing a DPP via the identification link and (ii) the AAS standard for structuring the information provided. This will enable the use of the standardized ÁAS model and its submodels to represent the product-relevant data and the standardized AAS API to provide and/or consume it.

Based on the DPP metamodel and the existing sources (e.g., product database), the DPP templates for all product and material types could be created semi-automatically. E.g., a tool could be developed to map the product/material structure of the existing sources to the DPP metamodel and the mapping rules should then be applied to create DPP templates for each specific product/material type. This could be done once at the launch of a use case and could be restarted on demand when new products/material types become available.

Besides the static aspects of a DPP that are the same for all products/materials of the same type (e.g., manufacturer), there are also some aspects that are unique for each individual product/material, such as energy consumption, carbon footprint or quality. These data should be collected/calculated in real time by a DT for process/production and "transferred" to a specific DPP instance at the end of the process.

[2] DPP 4.0 – The Digital Product Passport for Industrie 4.0 (dpp40.eu)

Since the energy equivalent or carbon footprint of a product is considered more important and different from the absolute energy consumption or CO_2 emissions during production, a method to distribute the value should be defined. Other factors that contribute to the CO_2 footprint during production could also be considered, such as the CO_2 footprint of the material, the logistics operations required, etc.

3.3.3 Ontology for modelling circularity-related aspects

The goal of a circular ontology would be to establish clear definitions of the concepts such as circularity, resource loops, waste management, eco-design, remanufacturing to ensure a common understanding among stakeholders. For example, it may describe how waste generation is linked to resource consumption, or how remanufacturing is connected to product design and material recovery.

Developing such an ontology would require collaboration and input from experts across different domains, including Circular Economy, sustainability, data management, and ontology engineering. It should be an iterative process, continuously refined and updated to reflect the evolving understanding and practices in the field of circularity. The well-known methodologies for ontology development (e.g., OnToKnowledge [54] should be followed and open source tools (e.g., Protege[3]) should be used for this purpose.

However, ontologies should not be developed from scratch. The existing ontologies should be reused. This helps avoid reinventing the wheel and ensures interoperability and consistency across different knowledge domains.

There are several existing ontologies and knowledge representations related to the Circular Economy. An overview of existing semantic models in the ICT, materials and CE domains is given in [55]. For each ontology, the authors present its purpose and scope, modelling language, conformance to best practices for ontology engineering, level of reuse of existing ontologies, availability, limitations and possible applications. The authors also found relevant catalogues such as the European Waste Catalogue (EWC), which includes waste categories to classify different types of waste based on their material composition.

The Circular TwAIn work on relevant ontologies is described in deliverable [56]. It will incorporate pertinent information about raw materials (virgin or secondary), including environmental and circularity aspects, from the very beginning of value chains and will facilitate the representation of a material and a product in a comprehensive, shared, and machine-readable manner across its lifecycle.

Since the circular ontology is the domain-specific ontology, it should be integrated and made available via generic, domain-independent Data Space components. This is the IDS vocabulary provider as it manages ontologies to enable understanding of the datasets/connector metadata. Indeed, the IDS vocabulary provider is a Data Space component that offers vocabularies (including ontologies) that can be used to annotate and describe datasets and connector/apps/services/resources. More information can be found at: [52].

At this stage of the Project, we do not see any technical challenge in integrating Circular TwAIn and other relevant ontologies into the Data Space vocabulary, in addition to the

[3] *https://protege.stanford.edu/*

challenges already solved by the IDS vocabulary provider component. However, as the Circular Economy is an evolving field and new concepts, technologies, and practices could emerge, the circular ontology is expected to evolve as well. Any change to this ontology needs to be propagated to the IDS vocabulary provider. A mechanism is required to ensure this synchronization. Additionally, we note here that some vocabularies/ontologies like eClass are available online and not via vocabulary provider. This however does not change the Circular TwAIn approach.

On the other hand, we assume an additional use of the circular ontology, namely the semantification of DTs. This is necessary for the case where the semantic IDs for the DTs are not specified. This "annotation" would increase the understanding of the AAS-compliant DTs when standard AAS submodel templates are not used. For more information, see the section 3.2.4.

Consequently, we do not expect development to consider the circular knowledge provided by the circular ontology. The focus is on modelling the ontology itself and using it to annotate the DTs and other relevant data sources.

3.3.4 DPP Registry

In section 3.2, we described the extensions that need to be made to register the available DT data in a Data Space. Here we focus on the DPPs.

For DPPs to be successfully implemented, stakeholders in the value chain should adopt a harmonized vision, information models, and practices. This requires the use of standards for modeling DPPs to ensure interoperability and enabling DPP data sovereignty to ensure trustworthiness between partners in a value chain. To realize this, there is a need for a DPP registry with onboard services to ensure the findability and accessibility of a DPP. The circular ontology (see deliverable [56] should be used to describe actors in the Data Space for Circularity, their interactions, the DPPs they exchange, and DPP data usage restrictions.

From a technical point of view, it should be clarified whether this will be a Data Space component (available via the IDS API) or a central DPP registry that uses the DT API. This depends on whether it is for one organization only or for all Data Space participants. If we assume that all DPPs are shared with IDS connectors, then this DPP registry could be implemented with the IDS Metadata Broker or it could be an AAS registry linked to the DTs available through IDS connectors.

By registering DPPs in a common registry, full traceability will be ensured throughout the enterprise and throughout the material/product lifecycle and the reusability will be guaranteed. The registry should offer functionalities to register DPPs, to find them, rank them according to their importance for the user's information needs, to notify the “interested” parties and to flexibly interact with them. Additionally, the registry can be also used for storing “abstract” DPPs (e.g., for a material type) that could be filled in with concrete values when creating a DPP of a concrete material. We note here that only the DPP metadata will be held and maintained centrally, the DPPs will be stored in a distributed way.

In the case that DPPs will be implemented based on the AAS standard, the already available implementations of the AAS registry could be used and extended if needed. This means that the already standardized AAS registry could store DTs and DPPs. This would accelerate development and ensure synergy effects.

3.3.5 Advanced services for circularity

Services could be divided into services that consider single DPP and multiple DPPs.

DPP services

The *governance services* should ensure that high DPP quality exists throughout the complete lifecycle of a DPP, and data controls are implemented that support Circular Economy objectives.

To ensure accountability for the negative impact of poor quality of DPP's data, the *data quality service* could be developed. It could improve handling of missing data by means of artificial intelligence/machine learning methods and/or anomaly detection methods.

To manage compliance with sustainability and Circular Economy goals, a *compliance service* could be developed. To address the dynamic aspects of the targets (e.g., due to supply chain disruptions or political situations), flexible means to support goal-driven compliance verification could be provided. These include, but are not limited to, various assessments (e.g., a financial assessment of the current and expected future residual value of materials), a calculation of the Circular Economy Index, etc.

In addition, *certification services* enable to demonstrate that that products and materials are compliant with national and international health, safety, environmental, etc. regulations (e.g., REACH) and standards. E.g., verification of compliance with environmental regulations (e.g., limiting the use of hazardous substances in products) could be supported to ensure understanding and control of a product's material composition. Moreover, reporting capabilities such as generating compliance certifications and reports could be provided to ensure materials/products can be sold in all relevant markets.

Value chain services

During the last years research and development was focused more and more on the reduction of energy consumption and/or emissions. These topics do not only concern one single production component vendor, but affect e.g., in the context of the carbon footprint calculation of a product the whole supply chain and lifecycle including many different parties. This explains the need for exchanging information in this field along the lifecycle and over company barriers. This requires collaboration and cooperation among DPPs.

The goal of value chain services is to help evaluate different alternatives for delivering a valuable material/product to the end customer from a Circular Economy perspective, thus improving the value of what is delivered. These include e.g., *track and- trace services* that help locate a DPP in a value chain.

The track and trace services should enable intelligent search in DPP value chains. They ensure traceability as they provide information about the route a material/product has taken from production through distribution to its destination. Whereas the tracking of a DPP will follow the path forwards from the starting point to wherever the DPP currently is, the tracing will follow the path backwards from its current point to where it began. The track and trace services will also consider the dependent DPPs by propagating search requests to all related DPPs that are results of merging, splitting, etc. activities and integrating their search results in an intelligent way.

Additional services could be also foreseen. E.g., the *simulation services* could be developed to estimate the technical quality, sustainability, toxicity, circularity of products/components based on included material, the *optimization services* could be based on multi-lifecycle assessments for accurate quantification of circularity potential for products made from secondary material, or *decision support services* could provide prescriptive analysis capabilities through optimization and simulation customized/developed across a value chain based on estimation of the average "circular contribution" of the different actors in the value chain.

3.4 Role of AI in the Data Space building blocks

The industry of de-manufacturing and re-manufacturing involves the processes of disassembling devices, testing the disassembled parts, and finally sorting healthy and unhealthy parts. In pursuit of this purpose, guided collaborative robots powered by AI algorithms can offer valuable benefits, such as increased disassembly productivity, identification of parts or subsystems, precise sorting, and assessment of material quality assurance. Moreover, AI algorithms facilitate decision-making regarding business progress and processes. Digital tools and information play a crucial role in the energy production industry. AI tools can help understand production process failures through their predictive capabilities. Additionally, AI tools offer predictive maintenance of assets and monitor various parameters during the production procedure.

Digital information is produced by both robotics and human operators. This information is helpful for AI algorithms to infer control and optimize the production procedure. Furthermore, the results of AI tools are available in the cloud service within the Data Space block for visualizing information regarding the production procedure for any use case. This information aims to provide end-users with a clear view of procedures and aid in decision-making about products and processes.

A Data Space architecture is designed to facilitate a self-governed method of data flow, that can be used for AI application on the edge (as previously mentioned) and cloud-based AI solutions. The role of AI in the Data Space building blocks is pivotal in revolutionizing the remanufacturing industries of computers/computer parts and EV batteries. By harnessing the power of AI algorithms, these industries can significantly enhance their processes and achieve greater efficiency.

The relevant components of the cloud layer in relation to the AI algorithm can be described as follows. Firstly, the data processing block encompasses a set of advanced tools and modules for data pre-processing. These tools enable the creation of high-quality datasets from raw data. Furthermore, there is the catalogues block which consists of two main catalogues. The ML/DL catalogue houses a vast collection of state-of-the-art machine learning and deep learning algorithms. It serves as a valuable resource for constructing artificial intelligence models from the ground up. Additionally, the XAI catalogue provides a comprehensive compilation of cutting-edge XAI techniques. It facilitates the exploration and implementation of advanced explainability methods. The XAI Trained models catalogue complements this by offering a comprehensive list of domain-specific AI models. Lastly, the XAI pipelines catalogue presents a collection of XAI applications (pipelines) that have been specifically developed for domains.

Moving on to the edge layer, we encounter the lightweight collaborative and explainable AI block. This particular component is a condensed version of the collaborative and explainable

AI module, designed for deployment on the cloud and optimized for edge devices with limited computing power.

Regarding AI in Data Spaces, there are several crucial requirements, namely provenance, privacy, and data governance. Provenance involves maintaining a thorough record of the data's origin and complete history. This is essential for ensuring accountability, traceability, and the reliability of AI models. Privacy plays a critical role, especially when dealing with sensitive data within Data Spaces. Robust access control and anonymization techniques are necessary to safeguard privacy. Lastly, implementing good data governance practices is vital to preserve the quality and integrity of the data.

3.4.1 WEEE and EV Batteries Pilots

In the remanufacturing of computers and computer parts, AI algorithms offered by both AI applications deployed on the edge and a cloud-based model catalogue that is part of the Data Space building blocks can facilitate the de-manufacturing procedure. Collaborative robots guided by AI can swiftly and accurately disassemble devices, identifying various parts and subsystems. The AI algorithms can then analyse these components, distinguishing between healthy and unhealthy parts with precision. These operations occur in the edge layer, that is also part of the Data Space ecosystem. This not only expedites the de-assembly process but also ensures that only high-quality components are selected for re-manufacturing, thereby improving the overall reliability and performance of the refurbished products.

Similarly, in the remanufacturing of EV batteries, AI plays a crucial role in the Data Space building blocks. AI algorithms can assist in the de-manufacturing process by efficiently disassembling the batteries and assessing the condition of individual cells. By analysing data from various parameters such as voltage, capacity, and internal resistance, the AI algorithms can determine the health and remaining lifespan of each battery cell. This enables the identification and selection of cells that can be re-used in re-manufactured battery packs, optimizing their performance and extending their operational life.

Further insights on the operation of both industries are available to the end-users by deploying advanced analytics, and AI plays an important role in learning from the historical values of the edge layer, thus enabling further optimizations of the remanufacturing chain. While the remanufacturing process of both pilots has a lot in common, the features of each use-case differ significantly, therefore the Data Space ecosystem can offer tailor-made solutions for each end-user.

3.4.2 Petrochemical Pilot

By leveraging AI algorithms and machine learning solutions, these plants can optimize their production processes, reduce energy consumption, and enhance overall productivity. The AI algorithms can analyse vast amounts of data collected from sensors and monitoring systems, enabling real-time monitoring and control of various parameters such as temperature, pressure, and flow rates. This data-driven approach empowers plant operators to make informed decisions and implement proactive measures (i.e., predictive maintenance, remaining use of life) to prevent equipment failures and process deviations, leading to enhanced operational efficiency and cost savings.

As previously stated, and to highlight the importance of the Data Space ecosystem, the Data Space can facilitate the intercommunication of different end-users without compromising the sensitivity of their data and provide a catalogue of a variety of models for the end-users to utilize the best model suited to their needs.

3.5 Remaining building blocks

In sections 3.2 to 3.4 several technical Data Space building blocks have been discussed that need extensions or customization w.r.t. DTs, Circularity or AI. The remaining building blocks (see Figure 10) do not necessitate changes regarding DT or Circularity since they include domain independent Data Space functionality. For the sake of completeness, we will give a short description of the remaining Data Space building blocks (i) data exchange APIs, (ii) identity management, (iii) trusted exchange and (iv) access and usage control/policies. Extended descriptions of these building blocks can be found in [1].

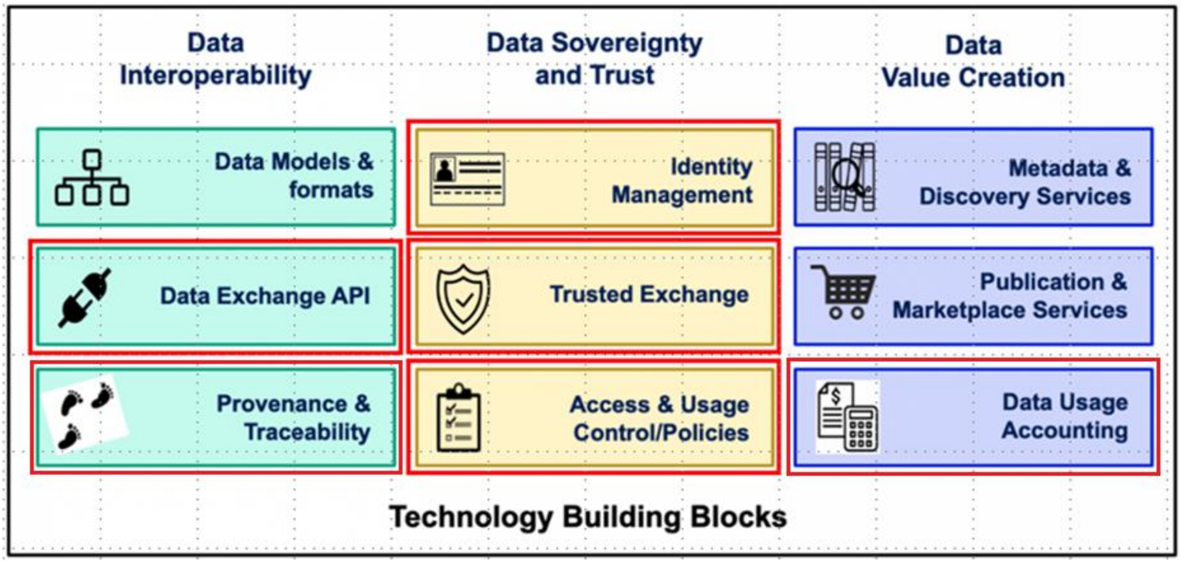

Figure 10: Remaining Data Space building blocks

3.5.1 Data Exchange APIs

This building block from the group of data interoperability blocks is used to facilitate sharing and exchange of data among different Data Space participants. Not only syntactic but also semantic interoperability must be guaranteed ensuring that the meaning of the data model within the context of a specific domain is understood by each participant of the Data Space. Furthermore, behavioural interoperability must be supported to ensure that that the results obtained by using the data exchange APIs achieve the expected outcome. Finally, the handling and interoperability of policies compliant with legal, organizational, and policy frameworks must be supported.

One example of a common data exchange API is the 'Context Broker' of the Connecting Europe Facility, which is used to share and integrate collected data including insights for further exploitation among multiple organizations. The Context Broker is recommended by the European Commission. Another example is the IDS Dataspace Protocol [9] which is used for the communication between IDS connectors.

The data exchange APIs building block is general for any data to be shared/transferred among any application among different Data Space participants. It should no need extensions or customization w.r.t. DTs, circularity or AI.

The remaining three building blocks deal with data sovereignty and trust. Also, these blocks are general enough to cover the requirements of DTs circularity and AI.

3.5.2 Provenance & Traceability

The feature of Provenance & Traceability is enabled by connectors logging data transactions and making them available in a central Data Space component. Special care must be taken when data is processed outside the connector or by 3rd party systems because such systems do not always provide data logs leading to dead-ends in provenance. Domain independent implementations found in connectors and usage control frameworks can be used here.

3.5.3 Identity Management

The identification, authentication and authorization of Data Space participants is managed by this building block. Each participant of the Data Space is provided with a unique and acknowledged identity which can be verified by authorization mechanisms to enable access and usage control. Individuals to be provided with these identities are organizations, people, machines, applications and other actors.

Examples for open-source solutions for the identity management building block are given in [1]: (i) the KeyCloak infrastructure, (ii) the Apache Syncope IM platform, (iii) the open-source IM platform of the Shibboleth Consortium and (iv) the FIWARE IM framework. Those identity management platforms are readily available and cover at least parts of the required functionality. Creation of federated and trusted identities in Data Spaces can be supported by European regulations such as EIDAS.

3.5.4 Trusted Exchange

Trusted data exchange is facilitated among participants of the Data Space. It is based on the identity management building block to assure that participants in a transaction really are who the claim to be and that the transaction is compliant with defined rules, policies and agreements. Usually this is achieved by organizational measures such as verified credentials (see identity management) or e.g., remote attestation.

A common example would be the IDS certification approach [47] where trust between unknown participants is created by using IDS certified software like connectors that conform to the defined rules and agreements.

3.5.5 Access and Usage Control/Policies

When data sources or services are published, they are usually provided together with usage policies as part of terms and conditions (see publication and marketplace services) or negotiated among the participants involved. The building block access and usage control/policies guarantees the enforcement of these policies to prevent misuse of data or services. Data access mechanisms are typically implemented by the data or service provider whereas the usage control mechanisms are implemented on the consumer side to prevent misuse of data or services. Access and Usage Control can be implemented by domain independent frameworks like MYDATA Control [57].

3.5.6 Data Usage Accounting

Lastly, Data Usage Accounting requires not only the Usage Control Framework but can also involve a centralized component where the data usage is recorded. In the IDS context, the IDS Clearing House [58] logs data transactions and usage to create bills and invoices.

4 Minimal Data Space for Circularity based on Digital Twins

4.1 Simplified high-level architecture with minimal set of building blocks

While the Data Space architecture shown in 3.1 mentions nearly all components a Data Space has to offer, they are not necessarily required for the operation of a minimal Data Space.

Figure 11 shows a Data Space architecture by the Eclipse Foundation which focuses solely on the necessary components [59]. A minimal Data Space usually only requires connectors and identity providers. For example, in a small Data Space for Circularity, participants browse the data catalogues of other participants by interacting with the data provider connector. Without a broker, the participants must know each other before data transfers and agree on the connectors and identities to be used.

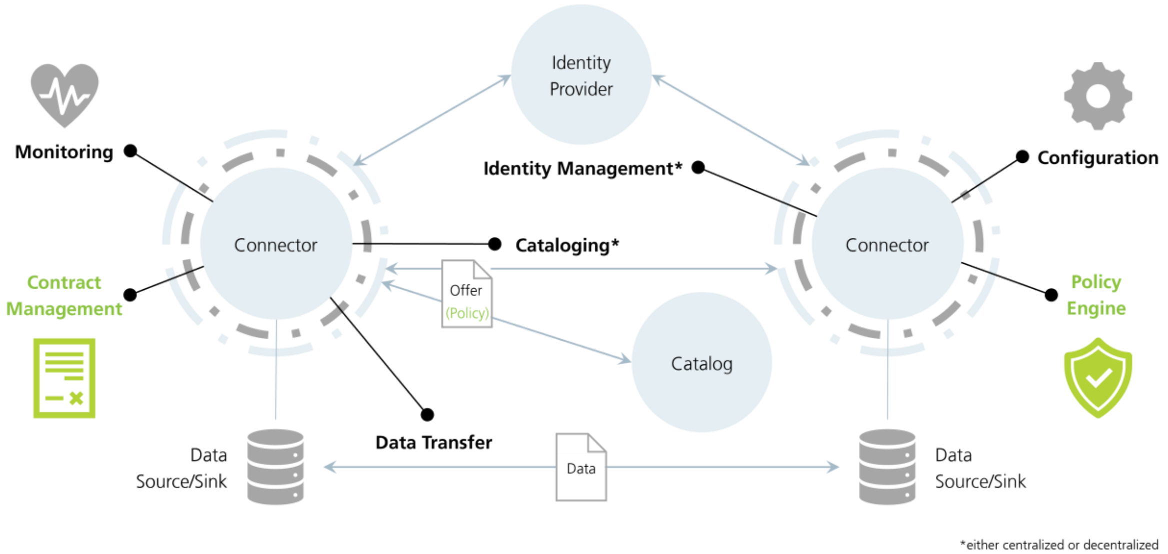

Figure 11: Connector in Data Space by Eclipse Foundation [59]

If we combine Figure 7 with the DT integration of Figure 8, we can leverage the AAS as data source/sink with several open-source implementations of connectors, identity providers and DT tools in a Data Space for Circularity. Table 4 shows the proposed software components and functions they provide.

Table 4: Software components in minimal Data Space for Circularity

Component	Function	Link
FA³ST Service	Provides an execution environment for the AAS	[60]
NOVAAS	Provides an execution environment for the AAS	[61]
TRUE Connector	IDS Connector for data exchange between DS participants	[45]
Eclipse Dataspace Connector (EDC)	IDS Connector for data exchange between DS participants	[59]

EDC Extension for AAS	Integrates the AAS into the EDC and simplifies AAS usage for providers and customers	[62]
Omejdn DAPS	IDS Identity Provider	[63]
EDC Identity Hub	IDS Identity Provider	[64]

The resulting architecture we propose and implement with these components is shown in Figure 12. The connector can be interchanged with TRUE Connectors in which case the control and data plane will be a unified one. The Identity Provider can also be realized by components like the Omejdn DAPS or EDC Identity Hub.

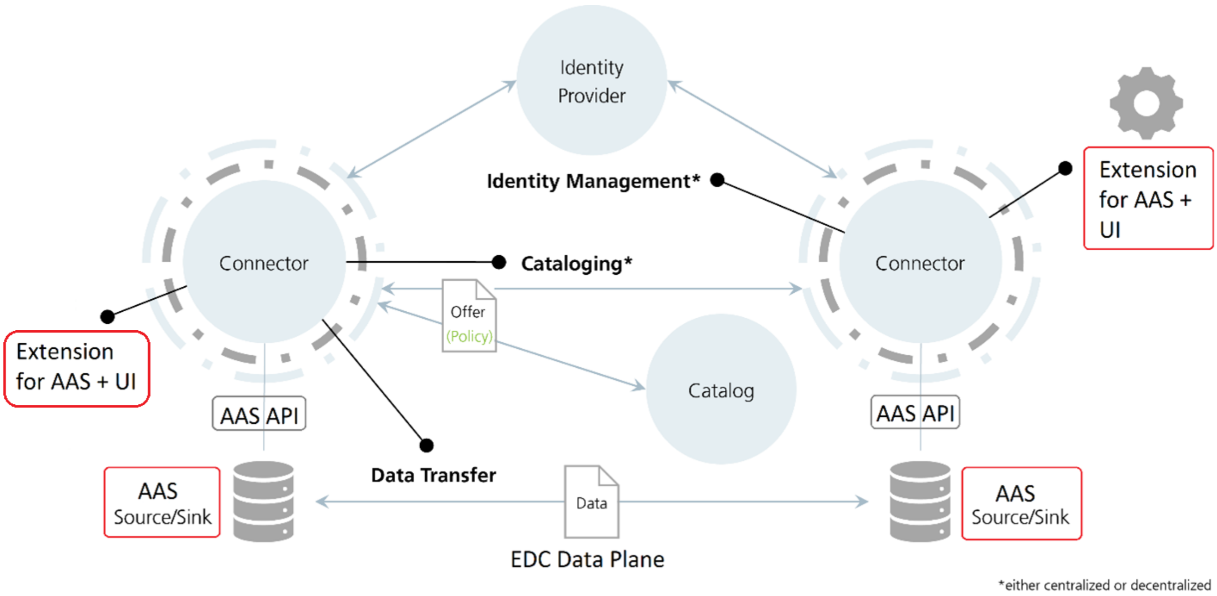

Figure 12: Minimal Data Space for Circularity (split data plane)

4.2 How to create an MVP circular Data Space based on Digital Twins

This section describes the steps needed to realize a circular DT-enabled Data Space.

4.2.1 DT modelling and creation

The first task is to model relevant DTs, e.g., with the AASX Package Explorer[4] or by coding. The DT model will be based on the AAS specification and the relevant sub-model templates.

Part 1 describes the AAS metamodel and serialization formats whereas the API specification for the is defined [15]. Figure 13 shows a simplified Unified Modelling Language (UML) class diagram of the AAS metamodel. In the AAS metamodel the main element is called *AssetAdministrationShell* which is linked to an asset (via *AssetInformation*). It consists of multiple *Submodels* which in turn consist of multiple *SubmodelElements*.

Submodels constitute the content of the AAS describing content-related or functional aspects of an asset. A *Submodel* in general consists of four areas described by SubmodelElements of different types: (i) general information, which gives minimal

[4] *https://github.com/admin-shell/aasx-package-explorer*

information about the provider of the asset and the asset itself, (ii) product classification, treating the asset as a commercial product to be brought to the market, (iii) technical properties describing technical data of the asset and (iv) further information, which may be additional textual statements by the manufacturer or e.g. date of validity.

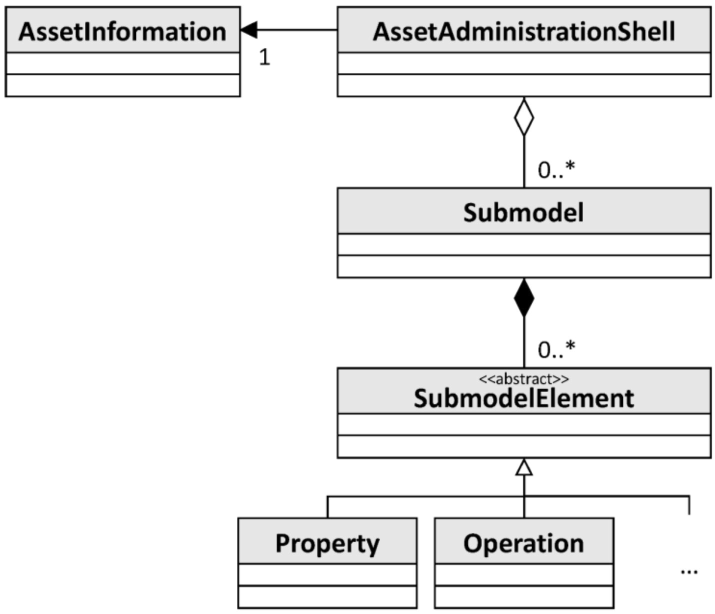

Figure 13: UML class diagram showing a simplified version of the AAS metamodel (taken from [20])

Submodels can exist independently of an AAS and can be used to develop different AASs. Currently the IDTA is developing many submodel templates to ease the development of submodels in a standardized way. The list of already released submodel templates contains very templates for different areas such as “Generic Frame for Technical Data for Industrial Equipment in Manufacturing”, “Handover Documentation” or “Provision of Simulation Models”. Furthermore, there are more than 40 submodel templates under development for diverse purposes such as “Maintenance”, “Part Traceability”, “Purchase Order Creation” or “Functional Safety”.

The most important submodel template for Circular TwAIn Project is the product carbon footprint submodel[5]. It is a result of joint work of ZVEI “PCF@ControlCabinet”[6] and the IDTA and is currently under review. It will provide the opportunity to share the carbon footprint of an asset between partners along a value chain. The idea is to increase the interoperability between the parties (e.g., manufacturers, consumers, logistic partners, end users, etc.), who are interested to document, exchange, evaluate, or optimize the environmental footprint of their assets.

The other submodel templates such as Product Related Environmental Data that aims to provide standardized, interoperable environmental data on the asset "product" for a wide range of applications or Facility Related Environmental Data that aims to establish a submodel with standardized, interoperable environmental data on an industrial plant, a

[5] *https://github.com/admin-shell-io/submodel-templates/tree/main/development/Carbon%20Footprint/1/0*
[6] *https://www.zvei.org/en/subjects/zvei-show-case-pcfcontrolcabinet*

facility and similar assets, will be also considered. More information can be found at [7]. If not available and required, some AAS submodel templates could be introduced.

The next step is to create the DT software counterpart based on the DT model and configuration file, if available. The configuration file defines how to connect to a physical asset (e.g., PLC of a machine), the relevant sensors and internal (e.g., MES) or external (e.g., EPCLA) software systems. The configuration could also be saved as an AAS submodel template, or even the AAS submodel templates currently under development could be used for this purpose. In this case, it is ensured that the configuration will be compatible with both AAS implementations used in the Circular TwAIn Project, namely FA^3ST and NOVAAS.

In this way, the DT software counterpart can be created without writing any code. The DT should be kept in sync with the real world in a protocol-agnostic way. Currently, OPC UA, MQTT and HTTPS are supported. For each asset specific protocol e.g., Siemens S7, the asset connection should be implemented.

Real-time data could be stored in the DT itself and historical time series data could be made available for data preprocessing and data analysis. In addition, DTs should be enriched with business logic to support services related to circularity. This includes incorporating rules and various models (e.g., data-driven, simulation and optimization models) that align with the circularity objectives.

The DT will also provide standardized AAS-compliant interfaces for the DT to interact with the outside world. Currently, the HTTP REST[8] and OPC UA[9] endpoints are specified in the AAS standard.

The final step would be to “connect” the DT to a Data Space for Circularity to enable cross-company exchange of DTs in a secure, trusted and semantically interoperable way. By extending DT/DPPs with IDS connectors, the DT-enabled Data Space for Circularity will be created that will ensure interoperability, provide privacy and security for this data, and allow value chain partners to control how this data is used. The Data Space for Circularity will provide the foundation for smart services and cross-enterprise business processes while ensuring DT/DPP owners' sovereignty over their content. More details on how this could be implemented is provided below.

4.2.2 DT integration with connectors

In this section we explain how a DT can be integrated with a connector. As it was decided to use the EDC and the TRUE connectors in the Circular TwAIn Project, we focus below only on these two connectors.

An example of integrating DTs & the EDC connector

Like previously mentioned, to share data in a Data Space, a description of data sources in the connector catalogue is required. This is mostly a manual process where the data to be shared is selected, described, and fitted with a usage contract. In the case of the AAS as a

[7] *https://interopera.de/teilmodellprojekte/*
[8] *https://app.swaggerhub.com/apis/Plattform_i40/Entire-API-Collection/V3.0*
[9] *The joint OPC UA and IDTA I4AAS working group has restarted its work on 05/06/2023 and will update the OPC UA endpoint based on the new version of the AAS metamodel and the AAS API.*

data source, each submodel or element requires such a description. Since the EDC can be extended with "EDC Extensions", we created an "EDC Extension for AAS" to simplify this process for data providers [62]. The extension also provides functionality for consumers interacting with AAS. Figure 14 shows the integration of the EDC Extension into EDC and the AAS as a data source.

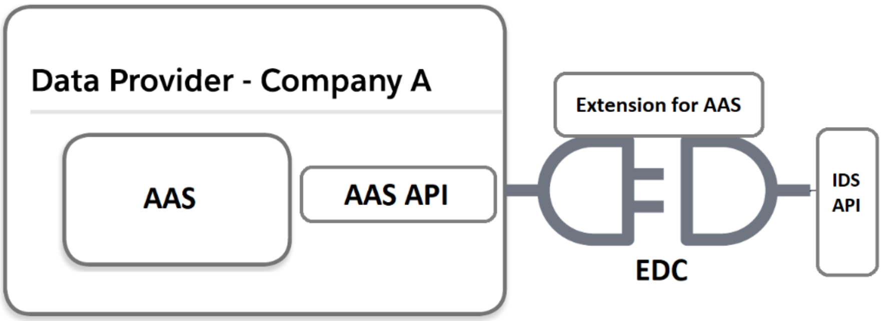

Figure 14: EDC Extension for AAS integrating AAS into DS

Data providers can simply upload their AAS or fill in the URL to automatically share the AAS over the EDC. When changes are made to the AAS of a product or process, the extension automatically updates the corresponding resources in the Data Space.

On the consumer side, we also simplified the request of AAS data and provide a user interface both provider and consumer. With the UI, consumers can browse the catalogue of other connectors and select suitable AAS data sources. The negotiation of the usage contract was also simplified for the consumer by clearly showing which contract the provider suggests and which contracts are accepted by the consumer.

In Figure 15 the architecture of the EDC extension is shown from a provider perspective. We differentiate between already running AAS (external) and AAS that will be started from a model file (internal). In the first case, the AAS is already running as a service in the company, for example with implementations like NOVAAS [61] or FA³ST Service [47]. In this case, the URL of the AAS must be provided so that all resources can be created automatically based on the external AAS. Initially, a default usage contract can be chosen, which will be applied to all elements to simplify the sharing process. Later, the contract can be modified for each element in the user interface.

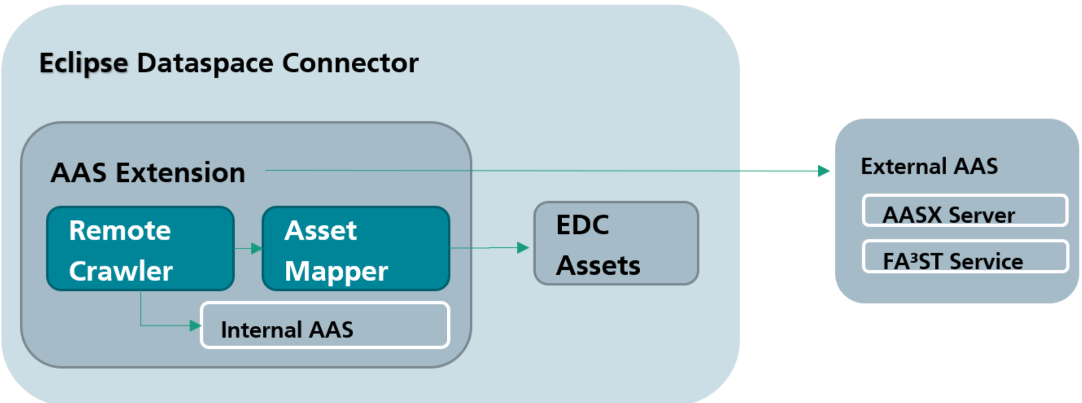

Figure 15: EDC Extension for AAS (provider view)

In the second case, the company does not have running AAS services (external). The provider can instead select an AAS model file that will be started as a service and shared automatically with the EDC extension. We use the FA³ST Service [47] internally to provide the AAS over EDC.

The extension is currently only supported in the EDC, since the EDC supports loading of extensions. It can be adapted for other connectors, e.g., TRUE Connector, for example by providing the functionality in an IDS App. In any case, a solution that fits all connectors is not possible since the software architectures differ.

An example of integrating DTs & the TRUE Connector

TRUE (TRUsted Engineering) Connector is an open-source implementation powered by Engineering and part of the FIWARE Catalogue. It is part of the IDS open-source catalogue, compliant with the IDS Reference Architecture Model (RAM3.0) and ready to be certified.

The architecture of the connector, following the RAM3.0, provides a strict separation between the Execution Core Container and the Data APP(s). As depicted in Figure 16, the Execution Core Container is in charge to exchange (physically) data and to interact with the Data Space infrastructural components in order to implement Access Management, Transaction Logging, Data Provider Discovery, etc.

On the other hand, the Data APP is the subcomponent in charge to integrate external systems (on both sides, provider and consumer) and to implement business logic for customizing the connector aiming to make it able to fit any kind of business scenario.

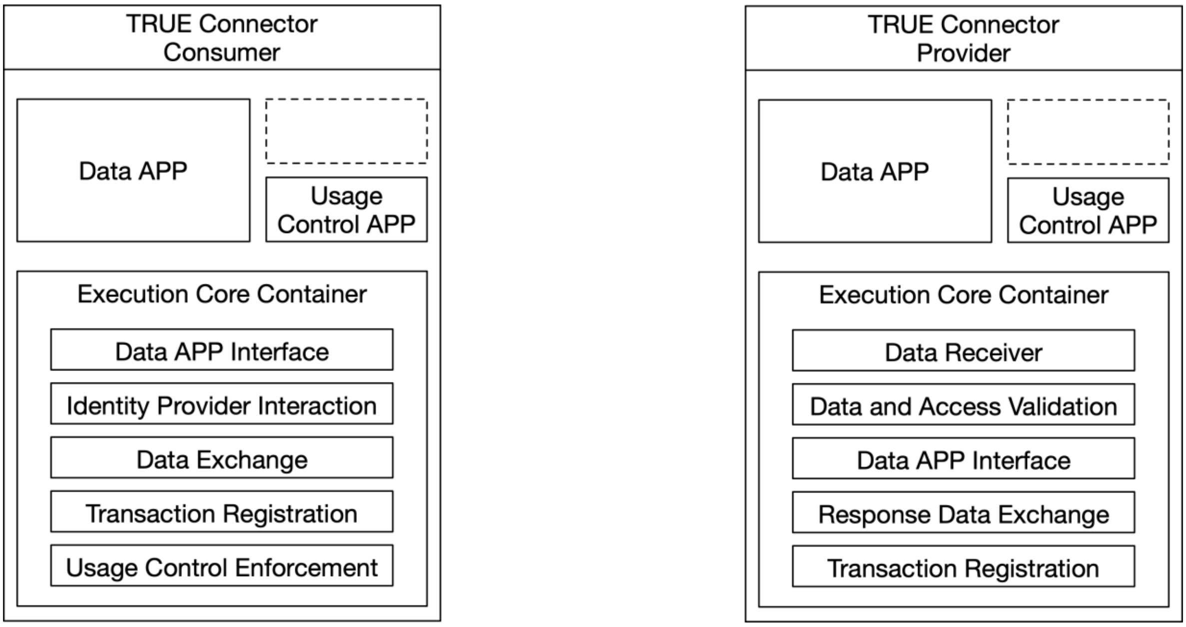

Figure 16: TRUE Connector Architecture

In the context of DT, AAS represents the standard to be followed and supported. Currently, the TRUE Connector can be used to exchange any kind of data and files in an agnostic way. However, in order to support AAS-based scenarios in a proper way, the TRUE Connector can be customized through a dedicated Data APP (i.e., AAS Data APP) to:

- Manage AAS files (both external and internal). AAS Data APP should manage persisted AASX files (i.e., docker volume) or to be able to fetch files from the remote backend system.
- Crawl AAS data (submodules and elements). In order to provide the data needed for the next steps, it is mandatory that the AAS Data APP parse AASX files, using a dedicated library, like eclipse-aas4j, to create a structure that can be mapped to artifacts or operations.
- Define an IDS mapping in terms of IDS artifacts. Once AASX data has been parsed, the mapping can be defined. The mapping will include the following:
    - for each element will be associated with static (default) usage policy, persisted on the file system (probably docker volume),
    - AAS Data APP will invoke TRUE Connector self-description API to modify/add new resources with a contract offer, so the consumer will be able to get the metadata and decide which artifact/operation would like to perform contract negotiation and get data or invoke operation.
- Associate Usage Control Rules to the created artifacts. If the default usage policy is not sufficient, the TRUE Connector operation user can modify a specific policy, via self-description API, and make necessary changes in terms of changing the default policy or adding a completely new one. The user can extend the start and end date, in which data can be consumed, and add the purpose of the data use, or the location in which data can be used.
- Enable the sovereign data exchange. Since a usage policy has been assigned to each resource, the interaction with the provider will have to be enforced via Usage Control. In that sense, the TRUE Connector usage control enforcement logic will be improved.
- Elaborate received data in order to make data available to a specific AAS implementation (i.e., FAST). The AAS Data APP will have to analyse and prepare received data for the targeting system/application. For this purpose, the FAST protocol (or some other, once a specification is known) can be supported/integrated.

4.3 Battery remanufacturing demonstrator

To validate our Data Space for circularity approach, we started implementing and setting up AAS-compliant DT and Data Space building blocks in our lab. Our goal is to provide a digital battery passport and a DT for the remanufacturing of batteries, including a carbon footprint for the remanufacturing process and each battery. This implementation should also be applicable for other pilots like the electronic waste and petro-chemical pilot.

First, an AAS- compliant DT for the battery and the remanufacturing process was modelled and instanced with FA³ST Service [47]. The recently released product carbon footprint (PCF) submodel template was introduced into the model to describe this aspect inside the AAS. We actively participated in the IDTA PCF working group and will continue participating in working groups related to relevant aspects of circularity. We also used the digital nameplate template along with our own process-specific submodels to describe the battery and the process, see Figure 17.

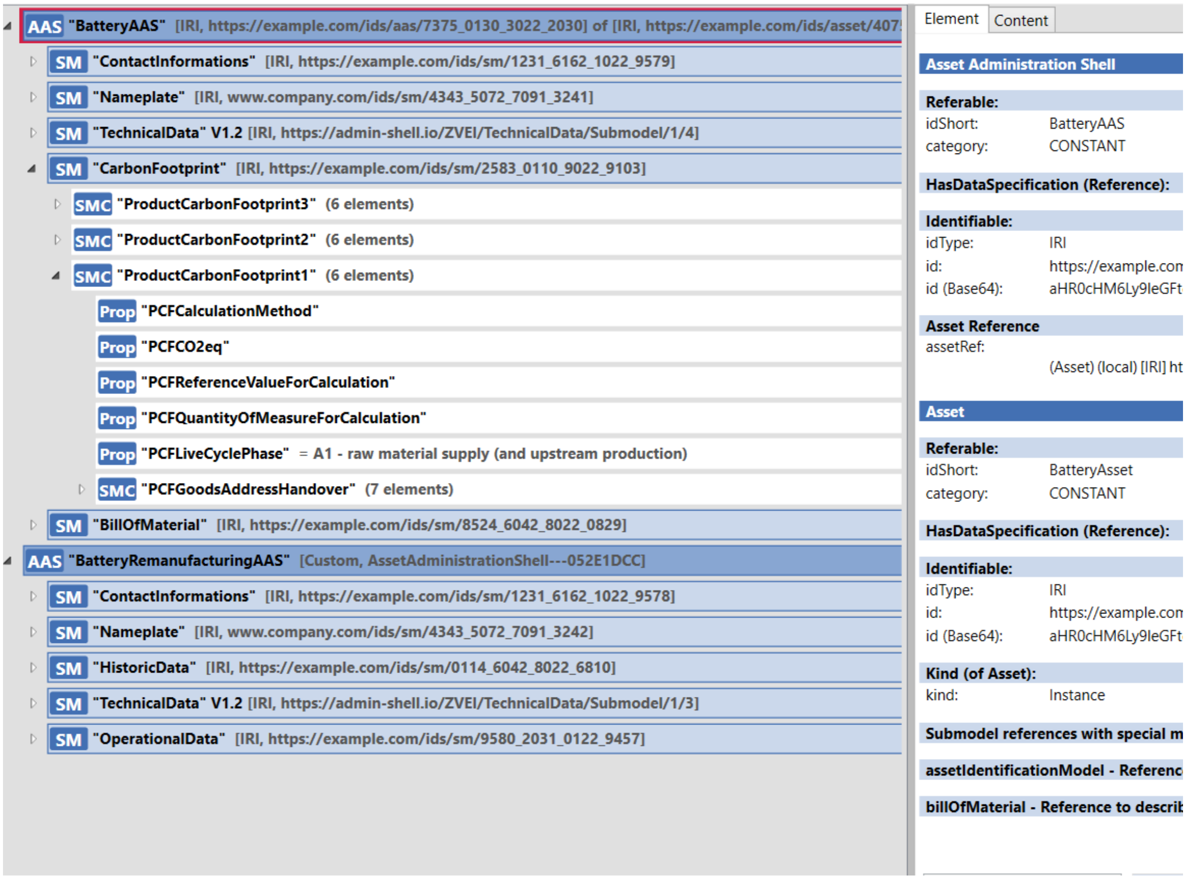

Figure 17: AAS for battery and remanufacturing process

To synchronize the battery and process data with their DTs, the FA³ST service offers the concept of “Asset Connections”, e.g., synchronization of process data via OPC UA servers or connections to data sources via HTTPS are possible with simple configuration of the service. We actively try to improve all aspects of the “Asset Connection” concept to support the Circular TwAIn pilots in implementing DTs and data integration. For example, a graphical UI can simplify the configuration of all DT connections for synchronization and is currently in development.

In our lab, we installed several power and air pressure sensors to simulate common sensor data in remanufacturing processes. The sensors are connected to a Siemens PLC and are, in our case, available via OPC UA. Assuming the remanufacturing of batteries requires power in the disassembly (power tools) or compressed air in the reassembly process (pneumatic impact wrenches), we simulated a CO_2 equivalent for testing purposes based on the German energy mix which includes fossil fuels. Based on the process duration, this CO_2 equivalent was then split onto each battery to estimate a CO_2 equivalent for the dis- and reassembly of a single battery.

The next steps involve the sharing of the battery and remanufacturing AAS in a Data Space. With the EDC Extension for AAS [62] included in our EDC, we inserted the link to the AAS provided our FA³ST Service in the extension UI, so that it will be automatically shared over the EDC. A default contract was chosen to be used as usage contract for all elements. Figure 18 shows the UI to select the AAS.

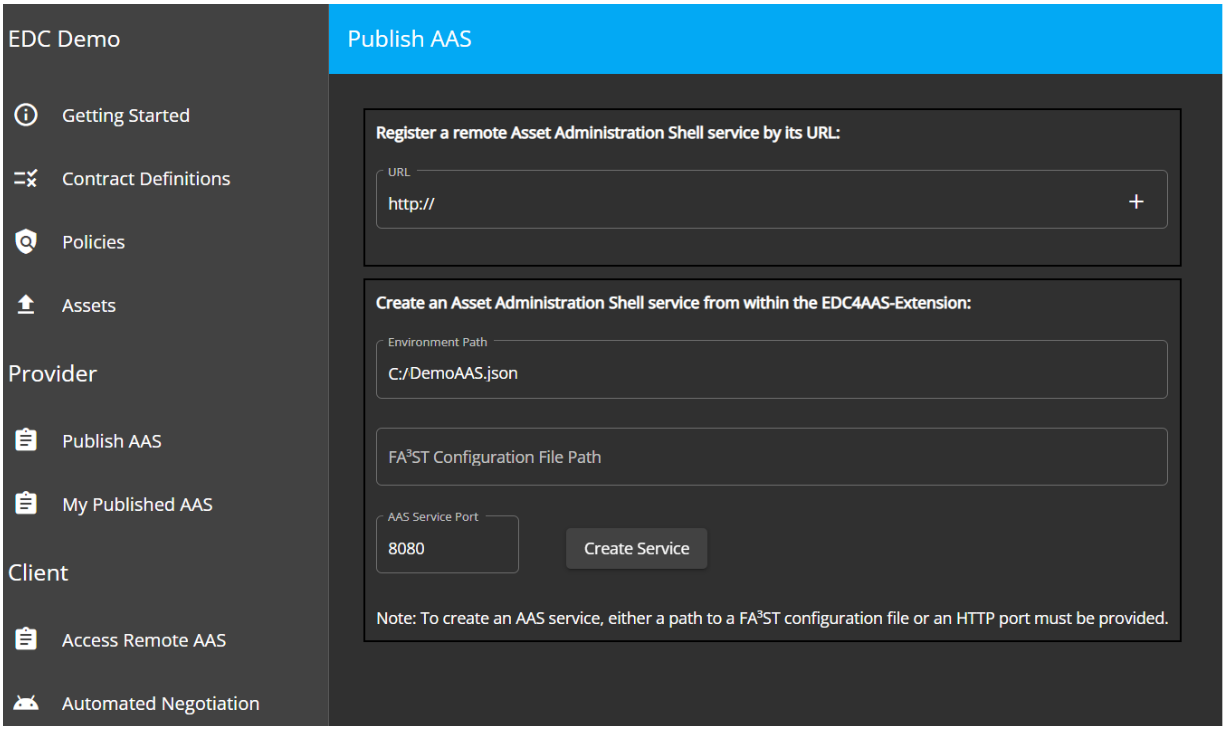

Figure 18: EDC Extension for AAS – provider UI

Figure 19 shows a consumer browsing and selecting AAS data sources provided by another EDC.

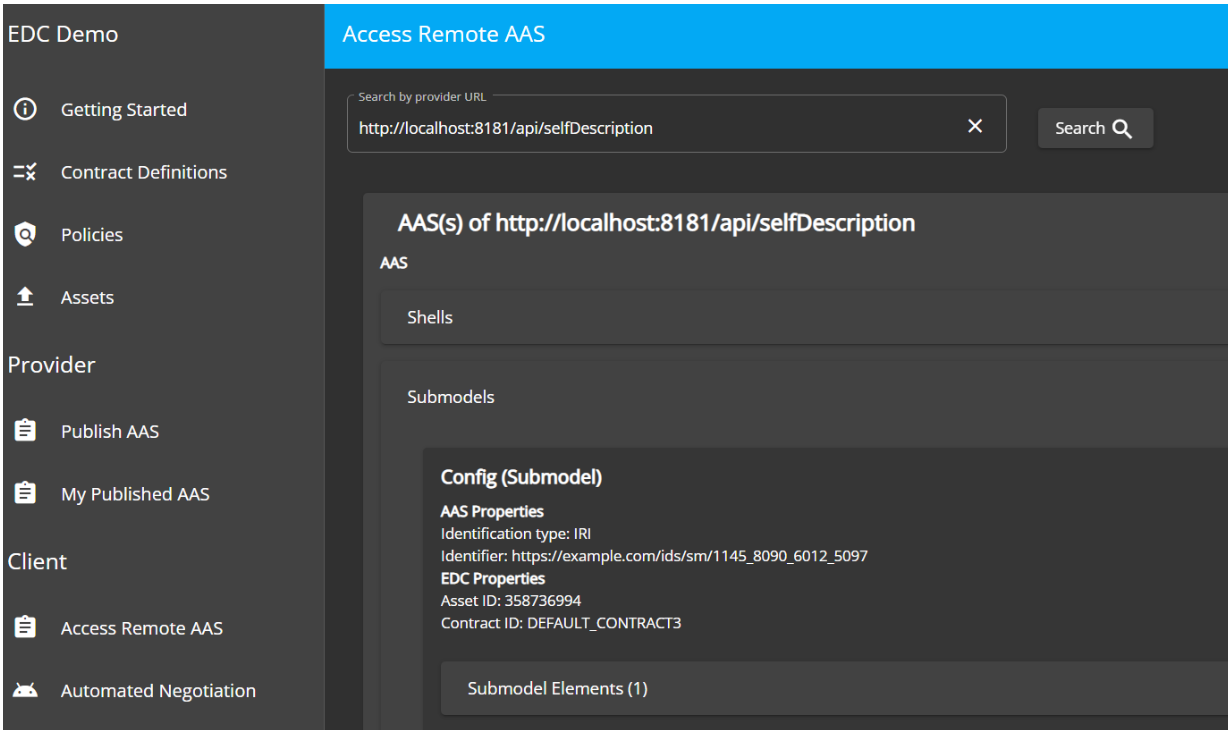

Figure 19: EDC Extension for AAS – consumer UI

For identity management, we used the Omejdn DAPS identity provider [63]. A certificate was generated for our EDC by this DAPS. A broker was not set up in the lab, but publicly available IDS brokers can be used in conjunction with a broker extension for the EDC [65].

Our next steps include the modelling of a complete battery DPP and remanufacturing process within an AAS and improving asset connectivity. The semantic IDs must reference newly developed ontologies from the Circular TwAIn WP4 tasks. Furthermore, the AAS requires more submodel templates to represent batteries and remanufacturing processes, which must be developed jointly with the IDTA. The AI models must be integrated into the AAS and Data Space.

Additionally, components like the EDC Extension for AAS must be created for the TRUE Connector and the incompatibility between TRUE and EDC connectors must be solved on both design and implementation level.

Both FA³ST and NOVAAS must be updated to the new AAS model and API version 3 and improved in asset synchronization and user friendliness to support the pilots.

5 Conclusion and Future Outlook

In this deliverable, we discussed technical building blocks in a Data Space for Circularity. As most building blocks are designed in a domain-agnostic way, the changes for a Circular Economy Data Space focus on the data modelling of circular-related data like carbon footprints or product passports. Also, the automated integration of this data into the Data Space with additional services or marketplaces are areas of particular interest which set different domain Data Spaces apart. Meanwhile, Data Space consortia like the IDSA provide generic building blocks and implementations, which can be leveraged for such domain-specific Data Spaces. We propose the modelling of circularity-related data with AAS submodel templates or referencing established ontologies or vocabularies within the AAS. For the registration of this data in the Data Space, we leveraged a generic EDC extension for the AAS to register AAS services as EDC resources. Similar extensions can be written for other IDS connectors.

The EDC extension requires further evaluation in the pilots and will be improved with additional user-friendliness as required in the pilots. Additionally, more aspect of the product and processes need to be modelled in the AAS with standardized submodel templates. We will continue our involvement in Industrie 4.0 working groups like the IDTA to specify these templates. The findings of this deliverable are necessary to implement the Circular TwAIn Platform with AAS and Data Space components. An evaluation of the building blocks will follow after implementation of the Platform.

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