AI Platform for Integrated Sustainable and Circular Manufacturing

Deliverable

D5.2 AI-enhanced Digital Twins Implementations for Products Production and Personae – 1st Version

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Definitions and acronyms

4IR	*Fourth Industrial Revolution*
AAS	*Asset Administration Shell*
CA	*Consortium Agreement*
AI	*Artificial Intelligence*
AM	*Additive Manufacturing*
API	*Application Programming Interface*
AR	*Augmented Reality*
BOL	*Beginning-of-life*
CA	*Consortium Agreement*
CI	*Collaborative Intelligence*
CI/CD	*Continuous Integration/Continuous Delivery*
CMMN	*Case Management*
CRM	*Customer Relationship Management*
CRUD	*Create Update Delete*
DL	*Deep Learning*
DS	*Data Space*
DSS	*Decision Support System*
DT	*Digital Twin*
DTMF	*Digital Twin Manufacturing Framework*
EC	*European Commission*
EDC	*Eclipse Dataspace Connector*
EOL	*End-of-life*
ERP	*Enterprise Resource Planning*
ESCO	*European Skills, Competences, Qualifications and Occupations*
EU	*European Union*
FDD	*Feature-Driven Development*
GA	*Grant Agreement*
GLN	*Global Lighthouse Network*
GPU	*Graphic Processing Unit*
GUI	*Graphical User Interface*
H-AAS	*Human Asset Administration Shell*
HDT	*Human Digital Twin*
HTTP	*Hypertext Transfer Protocol*
ICT	*Information and Communications Technology*
IDS	*International Data Space*
IDSA	*International Data Space Association*
IDTA	*Industrial Digital Twin Association*
IIoT	*Industrial Internet of Things*
IoT	*Internet of Things*
IIRA	*Industrial Internet Reference Architecture*
IT	*Information Technology*
KPI	*Key Performance Indicator*
LCA	*Life Cycle Assessment*
MES	*Manufacturing Execution System*
ML	*Machine Learning*
MOL	*Middle-of-life*
*O*Net*	*Occupational Information Network*
OEE	*Overall Equipment Effectiveness*
PDT	*Process Digital Twin*
PLM	*Product Lifecycle Management*
RA	*Reference Architecture*
RAMI4.0	*Reference Architecture Model for Industrie 4.0*
REST	*Representational State Transfer*
RTD	*Research and Technological Development*
SoS	*System-of-Systems*
SotA	*State-of-the-Art*
UC	*Use Case*
WEEE	*Waste Electrical and Electronic Equipment*

WoT	*Web of Things*
WP	*Work Package*
XAI	*eXplainable Artificial Intelligence*

Disclaimer

Executive Summary

This document presents the specification of the Digital Twins (DTs) in the context of circular manufacturing, focusing on three key aspects: product, process, and human. Circular manufacturing aims to create a closed-loop system where resources are maximized, waste is minimized, and products are designed for multiple life cycles where product, process and human DTs play the role of enablers.

Product Digital Twins are virtual representations of physical products that enable real-time monitoring, tracking, and optimization throughout their entire life cycle. By integrating data from various sources such as sensors, supply chain systems, and customer feedback, product Digital Twins facilitate improved product design, predictive maintenance, and optimized resource allocation.

Process Digital Twins enables real-time monitoring and analysis of production activities, to support continuous improvement of manufacturing operations and the implementation of circular economy principles.

Human Digital Twins focus on the workforce involved in circular manufacturing. By capturing data on employee skills, experience, and performance, human Digital Twins enable better workforce planning, training, and decision-making. They also facilitate collaboration and knowledge sharing across teams, enhancing overall productivity and innovation.

Implementing product, process, and human Digital Twins in circular manufacturing offers numerous benefits. It improves product design and quality, enhances resource efficiency, reduces waste, and enables more sustainable business practices. Real-time monitoring and predictive analytics empower companies to make informed decisions and adapt to changing market demands quickly. However, the adoption of DTs also presents challenges. Integrating diverse data sources, ensuring data security and privacy, and managing the complexity of DT ecosystems require careful planning and investment. Therefore, in Circular TwAIn a lot of time and effort have been invested in specifying a system populated by DTs to clearly identify the main features needed for satisfying pilot's requirements as well as for implementing circularity loops. Collaborative effort among industrial partners and technology providers have been made to establish a framework for designing DT and identify relevant standards to promote interoperability and scalability. The first version of the document is then focused on presenting:

1. the common approach used for building the specification of the DTs.
2. the concrete specification of the DTs based on a set of *Views and Viewpoints* for describing different aspects of the system.
3. how relevant industrial standards (such as Asset Administration Shell, etc.) oriented the design.

In conclusion, DTs provide a powerful framework for advancing circular manufacturing practices. Product, process, and human Digital Twins enable better resource management, more efficient production processes, and enhanced workforce capabilities. By embracing DTs, companies can transition towards a more sustainable and circular economy.

1 Introduction

As stated in [1], the current advances in Artificial Intelligence (AI), machine learning, robotics, high-performance hardware, and other technologies have increased and accelerated the pace of change drastically. According to [1], by 2025 50 billions of devices will be connected to the Industrial Internet of Things (IIoT), while 70% of manufacturers are expecting to be using Digital Twins in their facilities regularly to boost their production environments as well as to improve data integration for increasing the overall company agility. Here, the role played by Low-Code and No-Code technologies and platform is enormous in facilitating the development of new applications faster and often. With the pace and the proliferation of technologies organization are asked to be ready to incorporate and integrate within their solutions the most promising approaches and options. Considering the context, [2] identified seven industry-agnostic trends that matter most (see Figure 1-1).

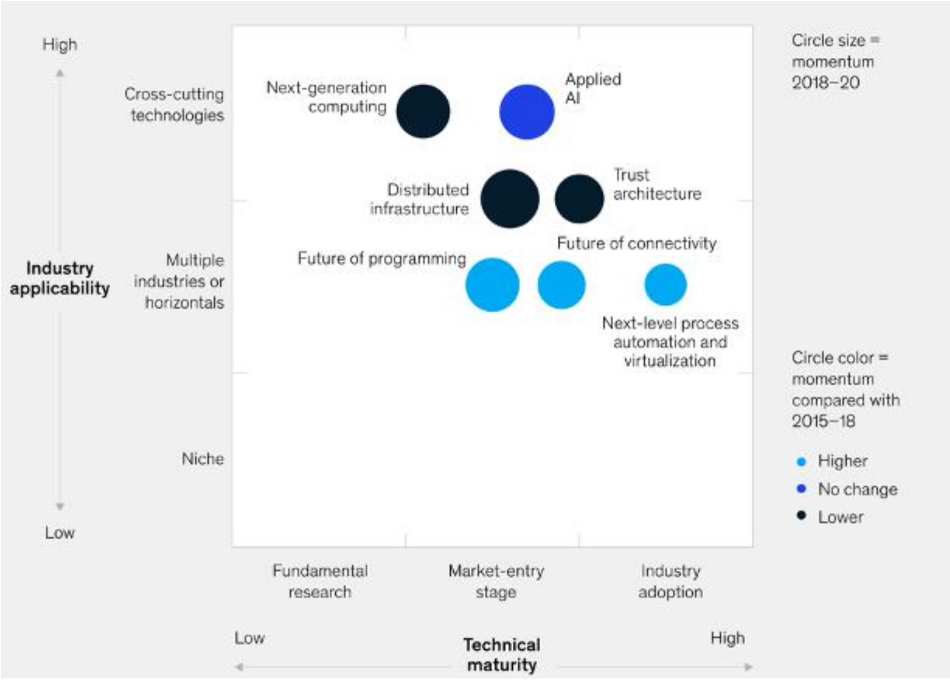


Figure 1-1. Industry-agnostic tech trends (adapted from [2])

The seven trends depicted in the Figure 1-1 are fully aligned with the Circular TwAIn objectives and represent the pillars of the work that is being developed in the context of the WP3 where the main focus and objective is how to push and – thus – apply these trends across industries in order to produce the biggest implications on companies competitivity, digital capabilities and overall performance. The seven trends are listed below:

1. Process automation & virtualization: design and development of the next-generation of production system strongly based on IIoT, robotics, Digital Twins and simulations will impact the way processes are designed and operated. Production can gain scalability, improved resource productivity, faster and more flexible processes, higher material productivity. All these aspects together will deliver a better characterization of the products, product life cycle assessment, (re-)usage of input materials, etc. while supporting the circular economy.
2. Future of connectivity: improves connectivity allows Digital Twins solutions to be responsive in data extraction, collection and provision. These enable a better and

well-informed and more accurate decision processes. In processes, product and human superfast connectivity open the door to more robust and well-monitored processes, new business models, services and condition monitoring for products, as well as, next generation of user experiences (virtual, augmented reality, industrial metaverse) when interacting with the process.

3. Distributed Infrastructure: distributed computing paradigms (e.g. cloud and edge computing) enable Digital Twins to reach data with far-less latency and in a greater number of location. These in turn will enable company to deploy more modular solutions that can target specific and concrete business goals such as digitalization of processes, higher innovation, reducing costs and improving product quality, improved operations, etc.
4. Next-generation of computing: high computational capabilities and high-performance hardware are the foundation for the deployment at scale of AI-enabled use cases. AI-enabled/empowered Digital Twins require advanced hardware platform to support adaptive systems to take decisions during the production process operations.
5. Applied AI: applied AI is the necessary condition for building smart/intelligent applications that rely on computer vision, machine learning, optimization algorithms etc to improve/optimize processes by eliminating repetitive tasks as well as automating manual tasks. Therefore, Digital Twins must support the execution AI models.
6. Future of programming: it is related with the “Software 2.0” concept where the development tasks are supported by AI (i.e., chatGPT). Moreover, the way the software is built relies on low-code and/or no-code development platforms. In this landscape, in Circular TwAIn we are envisioning the usage of such platforms for both software as well as AI-based solutions development. The trend makes possible the scaling and spread of AI-based applications.
7. Trust architecture: even if this trend is more related to cyber security, in the context of Circular TwAIn we are interested in sharing data in a way that companies can control. Therefore, Digital Twins are asked for integrating the necessary mechanisms to enable the secure and trustworthy data sharing across companies and industries.

Saying that, the document presents the work done by the Circular TwAIn partners in connecting these trends to the pilots and describes:

1. how fundamental technologies like Digital Twins can drive the business, i.e., how technology can be adopted and deployed within brown field environment to really change the business strategy of the companies and help them in creating value.
2. the need for a new operating model where loosely coupled components are designed to easily interact with each other within a common environment that facilitates the adoption of agile software development methodologies.
3. How to use technology to address and include circularity aspects need.

2 Research Method

The implementation of Digital Twins (DTs) must be supported by state-of-the art methods and techniques used to build other products and/or services. The design of DTs can vary across three main dimensions, namely:

- Scope: to clearly identify the scope of the DT. The DT can be designed to cover very specific aspect of a product, process and/or personae. The narrower the scope of a DT, the more precise virtual representation will be. Especially in the case of product and processes, the design granularity assumes a fundamental importance. As a matter of fact, a product/process are today inherently complex systems that can be made-up of several systems, multiple sub-systems, and hundreds of components (considering the hierarchy of complex systems). The way we decide the design granularity will impact the manageability of the DT analysis to be performed.
- Value Chain: to identify for each one of the envisioned DT the value chain steps that the DT will cover. The identification of the value chain steps will force the establishment of the boundaries between the DTs as well as the recognition of the necessary interfaces. As a matter of fact, a production DT could incorporate data from production system subsystems and components, materials, results of tests and quality checks. A service/product DT could potentially incorporate data collected during the product use such as maintenance history, performance assessments, diagnostic information, etc. Since any industrial cannot operate without the human active participation then they should be considered as an integral part of the system. However, the lack of control over human operators implies that a possible human DT should be focused on collecting on how the human interact with the system and on providing the necessary information to facilitate the huma activities while minimizing the impact of the human on the system performance.
- Sophistication: for each one of the DTs different levels of sophistication can be considered, ranging from simple data integration and routing to closed-loop real-world link. Here the focus should be in finding the correct balance between performance and schedule constraints, i.e., the focus is to deliver a system that meets both the requirements and the development objectives in the defined time-schedule.

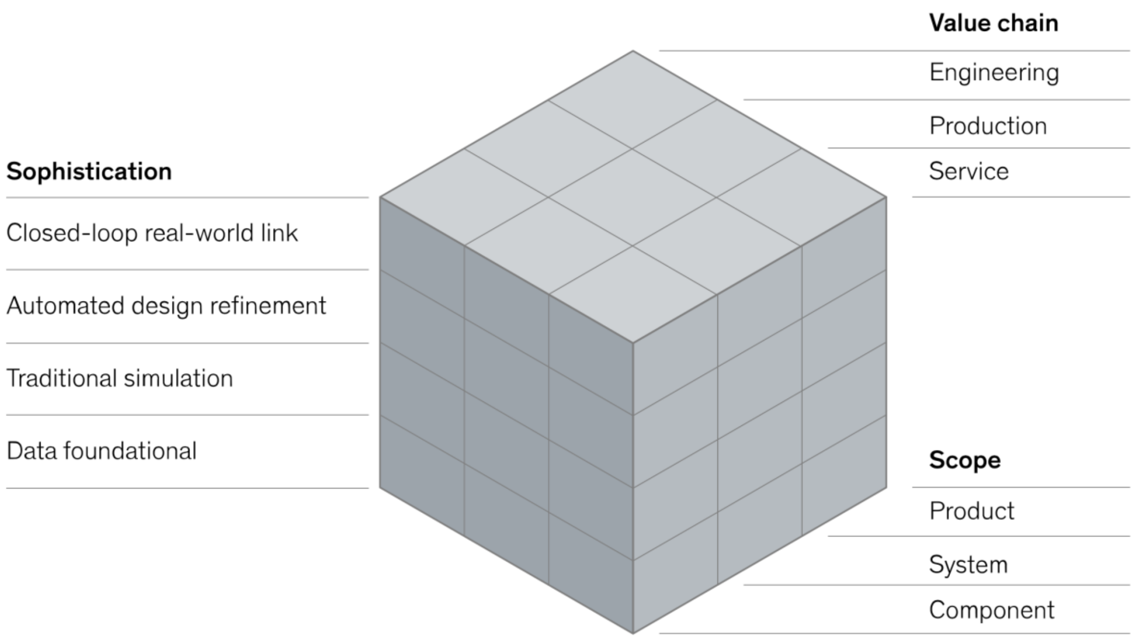


Figure 2-1. Design of Digital Twin across three dimensions (extracted from [3])

Organizations that want to take advantage with DT adoption must assess, select and focus their DT developments to really enhance technical and to reach business objectives.

Due to the complexity in designing DTs, this document is aimed at providing a common methodology to be used to drive the design phase and – thus – the implementation of the DT for product, production, and *personae*. Saying that, the proposed Concept and Engineering Development Process methodology is built on the following interconnected activities, namely:

1. Concept Development & System Specification: it is the initial development activity that is aimed at defining a system concept to best satisfy a specific need. This activity implies the analysis and planning that is necessary to establish the need for the new system, the feasibility of its realization and the specific system architecture to best satisfy the user needs.
2. Architecture Design: The analysis and process plan performed in the previous activity will be used as the foundation of the system architecture design activity where the following sub activities will be performed:
    a. Definition of the interaction between the physical and digital dimensions.
    b. Definition of the system layers and components.
    c. Definition of the data model.
    d. Definition of the process (the DT in context), Interfaces (externals and internals) and dependencies.
3. Engineering Development: the activity is aimed at developing a system considering the designed architecture to satisfy the identified requirements. Here agile software methodologies are used to continuously develop and test a minimum viable product (MVP) of a list of prioritized features.

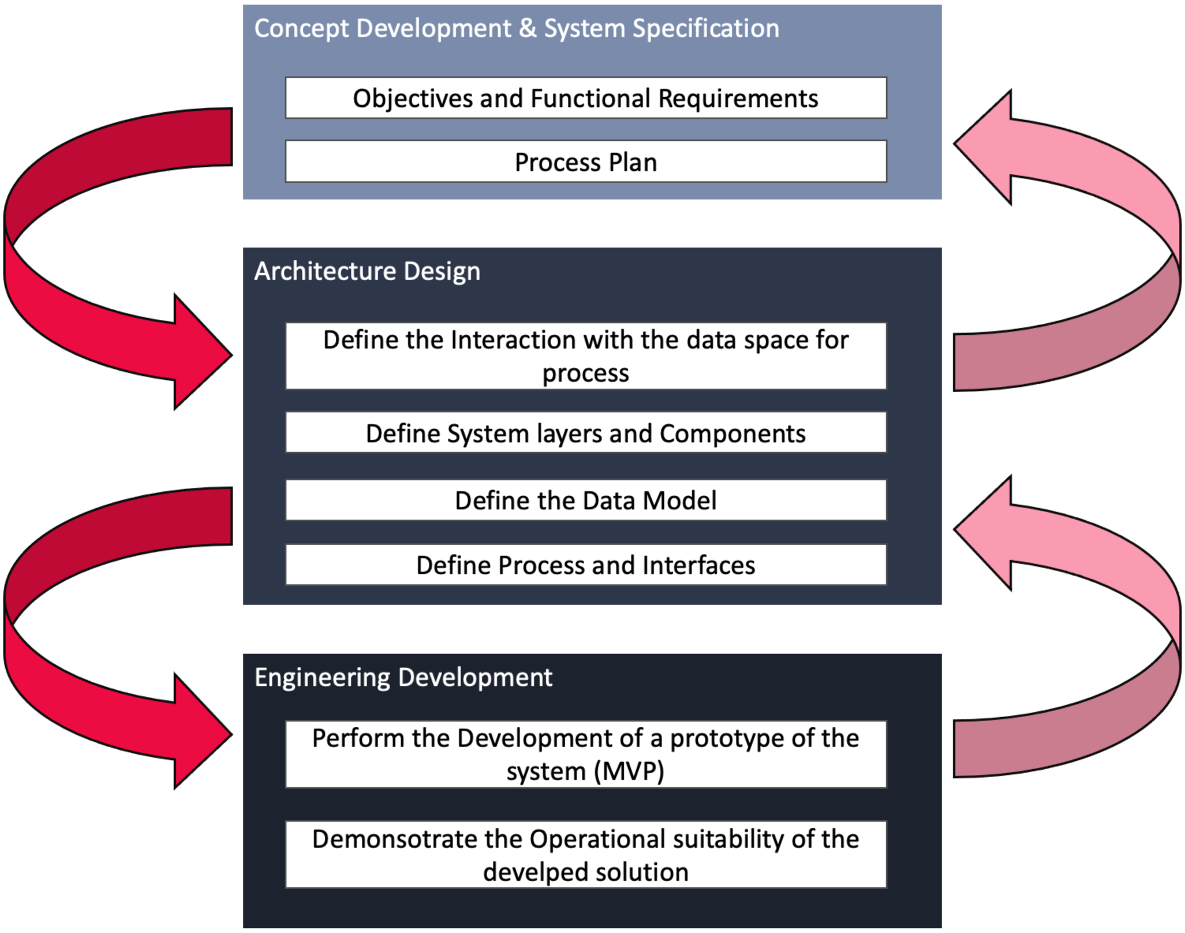


Figure 2-2. Proposed methodological design of Digital Twins

3 Theoretical Framework

This section is aimed at showing the theoretical framework for guiding the design and development of the three types of DTs that the Circular TwAIn Project will cover. The proposed theoretical framework will be based on a set of existing models, theories and ideas that will be used to facilitate the employment of the methodological design presented in Figure 2-2.

3.1 Concept Development & System Specification: Dimensions to Consider

The first step of the process to design and build a DT requires the modelling of all the static properties of the system. This step is aimed at formulating and defining a system concept to best satisfy a valid need. This concept development embodies the initial analysis and planning that will highlight the need for a new system while setting the foundation for the system architecture. Thus, during the stage the operational needs will be translated into a technically and feasible concept.

The development of a system concept requires knowledge about the domain of application, specific execution environment, as well as about integration, interoperability and data modelling, security & trust, etc. To facilitate the way this knowledge is captured, organized, and structured a simplified version of the RAModel (see Figure 3-1) is used.

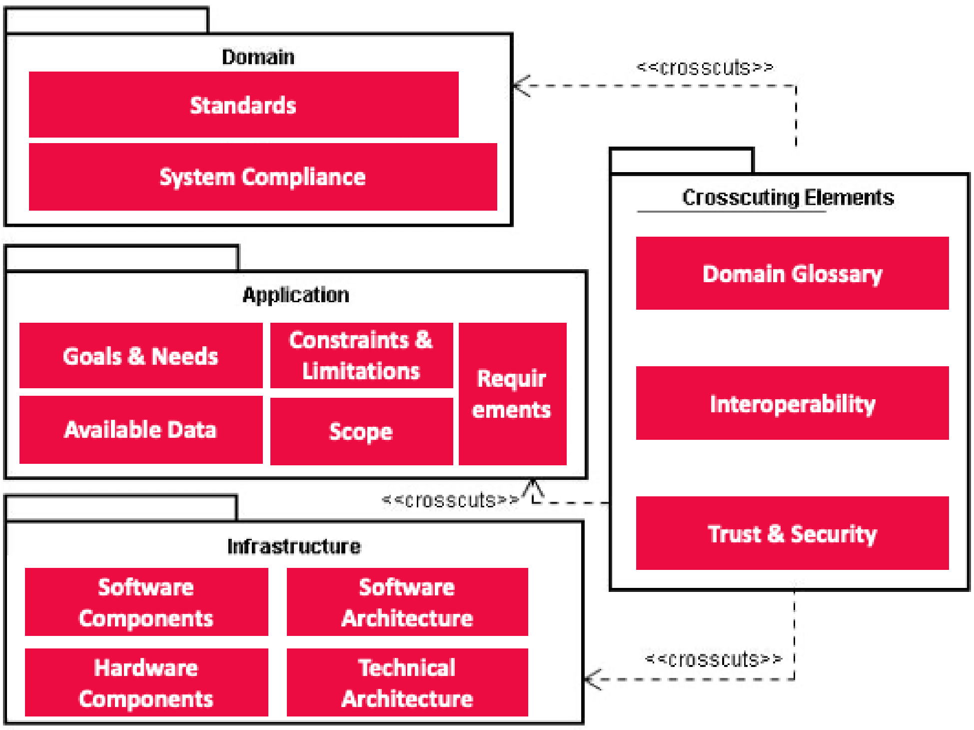


Figure 3-1. Simplified RAModel to be used for Concept Development & System Specification (adapted from [4])

The model contains all the important elements for developing a system concept and guide the design of the system architecture. The model is built around four main perspectives that are representative of the most interesting characteristics and dimensions to be analysed during the system engineering process. The Table 3-1 presents these dimensions with more detail.

Table 3-1. Considered Dimensions for Concept Development & System Specification

Domain Elements	
Standards	Standards existing in the domain that should be present in systems resulted from the architecture
System Compliance	Means to verify if systems developed from the architecture follow existing standards
Application Elements	
Goals & Needs	Intention of the architecture and needs that could be covered by the architecture
Constraints & Limitations	Constraints presented by the architecture and/or constraints in specific part of an architecture. Limitations presented by the architecture and/or limitations in specific part of an architecture
Scope	Scope that is covered by the architecture, i.e., the set of systems developed based on the proposed architecture
Requirements	Set of functional requirements that are common in systems developed using this architecture
Available Data	Common data found in systems of the domain. These data are presented in a higher level of abstraction, considering the higher level of abstraction of the reference architecture
Infrastructure Elements	
Software Components	Elements of software present in the architecture, e.g., subsystems and classes, which could be used to develop software systems
Software Architecture	General structure of the system architecture, represented sometimes by using existing architectural styles
Hardware Components	Elements of hardware, such as server and devices, which host systems resulted from the architecture
Technical Architecture	Development and deployment view of the architecture, a more concrete view (e.g., tools, tech stacks, etc) of the proposed software architecture
Crosscutting Elements	
Domain Glossary	Set of terms of the domain that are widely accepted by the community related to that domain and are, therefore, used in the description of the reference architecture
Interoperability	Exchange of information between the systems resulted from the architecture and the external environment. Exchange of information among internal part of the systems resulted from the architecture
Trust & Security	Set of issues that must be considered and addressed in the architecture to enforce and control the data exchange /transfer

The Figure 3-2 shows how the considered dimensions are used to guide the development of three technical handbook (Tech HB) that are live documents that will gather all the design and development activities of the three envisioned DT.

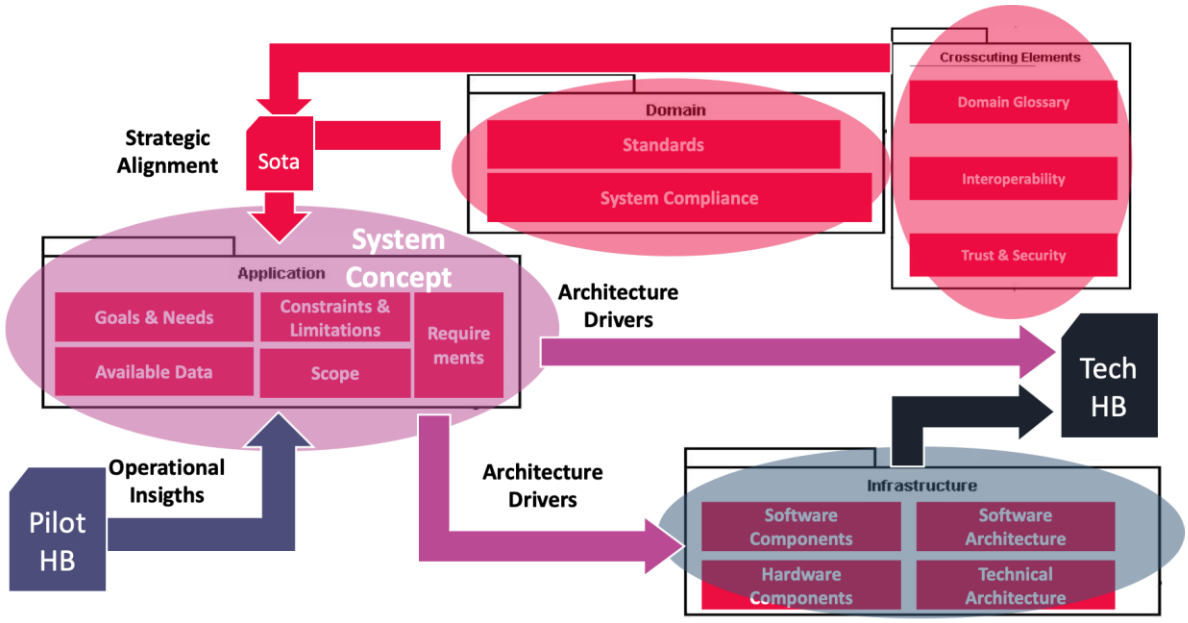


Figure 3-2. Expected Input/Output of the System Concept Development & System Specification and relation with RAModel dimensions.

According the Figure 3-2 , the principal objective of the concept development are:

- Establishing the need for a new system. Here, the Pilot HB will provide a fundamental contribution for doing that. Specifically, the pilot HB will provide operational insights for characterizing the system in terms of functionalities, performances, etc.
- Explore potential system concepts and already developed solutions. Here the Information and Communications Technology (ICT) vendor in the consortium will provide strategic alignment and insights with/into the market available solutions, including own products, and into the state-of-the-art of corresponding applications.

The main result of this stage is a set of architecture drivers that need to guide the Architecture Design stage. Considering that, the proposed approach for System Concept Development & System Specification combines a top-down and bottom-up approaches (as shown in Figure 3-3). The former is aimed at describing the domain, define the application context, and identify the core functionalities and main features of different families of DTs. The latter is aimed at particularizing and further specifying the identified generic and core functionalities and features by taking into account the needs, operational context, technical requirements, available data sets. This is a fundamental validation per se since it ensures the industrial acceptance of the proposed solution and its implementation by all the involved stakeholders (e.g., system integrators, components/device providers and manufacturer).

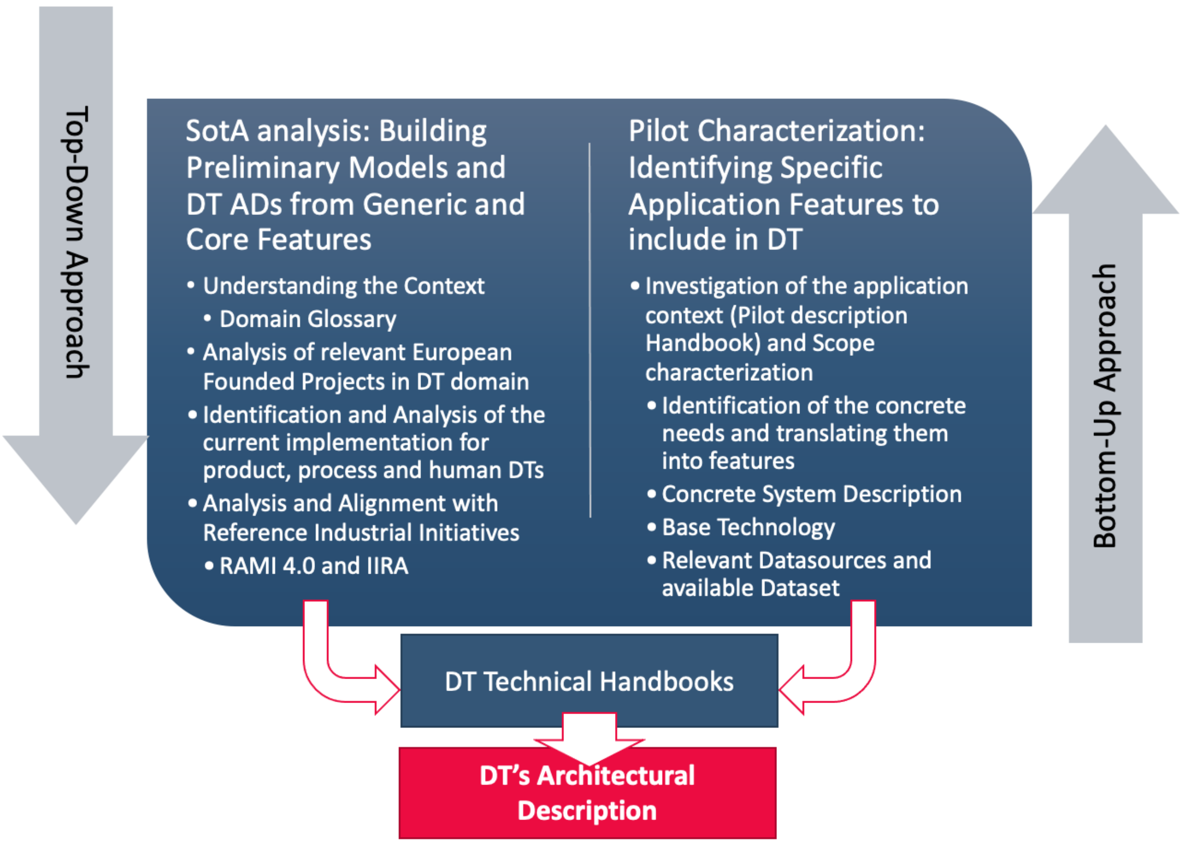


Figure 3-3. Approach applied in Circular TwAIn requirements analysis

3.2 Architecture Design

Once the Concept Development & System Specification is done the Architecture Design step of the process can start. During this step an overview of the main conceptual elements and candidate building blocks of the envisioned IT system's architecture is provided together with their interrelationships in the architecture are provided. The steps followed for building a software architecture are presented in Figure 3-4.

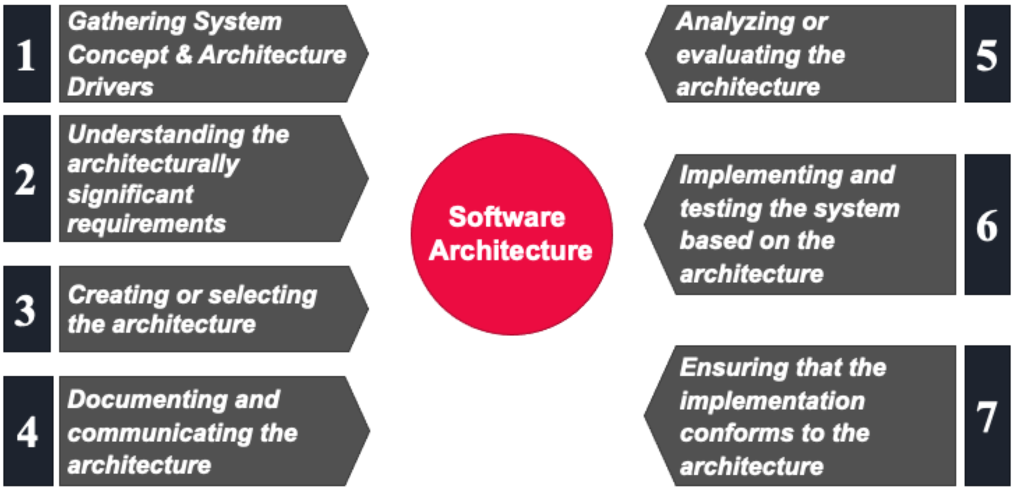


Figure 3-4. The main steps for building the DT software architecture.

For the architecture definition process to be successful it is necessary to be strictly aligned with the goals set up for the IT system to be developed. The *Gathering System Concepts & Architecture Drivers* step has the objective to deliver a preliminary and high-level description of the system and/or components to be implemented as a part of the overall IT strategies of the considered pilots. Therefore, the outcome here is the description of the necessary IT capabilities required by the organizations to support the system that is to be built. Since the architecture forms the bridge between the system requirements and the software system development then *Understanding the architecturally significant requirements* is a necessary condition for the correctness and the goodness of the model. During this step the identification and the characterization of the key stakeholders' concerns is fundamental for building and consolidating the model of the envisioned system. After the first two steps, the focus will be the creation and description of the architecture (steps 3 and 4 in the Figure 3-4). To model and design an architecture description of software-intensive systems we suggest an evolution and development of the "4+1" view model [5] that includes the following set of views/viewpoints (viewpoint catalogue): i) Context, ii) Functional, iii) Information, iv) Concurrency/Process, v) Development, vi) Deployment, and vii) Operational. As a matter of fact, a complex system can be easily and more effectively described by using a set of documents and+/or models that collectively demonstrate the static and dynamic behaviour of the system and how it meets its goals.

The relationships between the views, as well as the explanation of each one of them are presented in Figure 3-5 and Table 3-2 respectively.

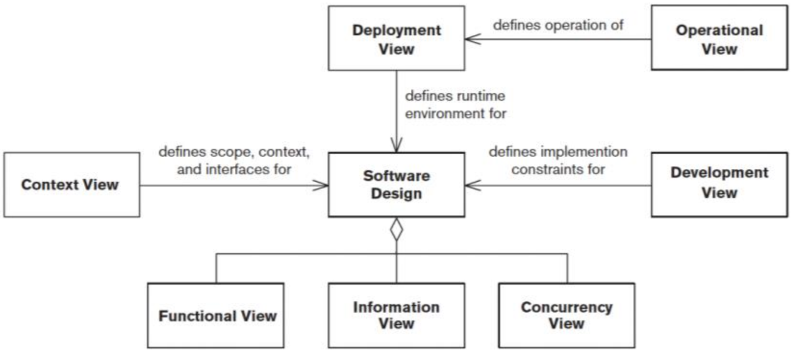


Figure 3-5. Relationships between the considered set of views/viewpoints

Table 3-2. Viewpoints & Views Explanation

Context View	Describes the relationships, dependencies, and interactions between the system and its environment (the people, systems, and external entities with which it interacts).
Functional View	Describes the system's runtime functional elements, their responsibilities, interfaces, and primary interactions. It is the cornerstone of any AD. It drives the shape of other system structures such as the information structure, concurrency structure, deployment structure, and so on.
Information View	Describes the way that the architecture stores, manipulates, manages, and distributes information. The ultimate purpose of virtually any computer system is to manipulate information in some form, and this viewpoint develops a complete but high-level view of static data structure and information flow.
Concurrency /Process View	Describes the concurrency and synchronization aspects of the architecture. This entails the creation of models that show the interprocess communication mechanisms, state management, synchronization, etc. However, the focus here will be on interprocess communication.
Development View	Describes the architecture that supports the software development process.
Deployment View	Describes the environment into which the system will be deployed and the dependencies that the system has on elements of it. This view captures the hardware environment that your system needs (primarily the processing nodes, network interconnections, and disk storage facilities required), the technical environment requirements for each element, and the mapping of the software elements to the runtime environment.
Operational View	Describes how the system will be operated, administered, and supported when it is running in its production environment.

Once the architecture is described from all the perspectives by using a set of separated but interrelated views and related viewpoints the step 5, 6 and 7 can be performed. These three steps are strictly connected and aim together at evaluating architectural options by highlighting the strengths and weaknesses of the chosen solution. As part of these steps, a skeleton of the system is provided that will act as evolvable prototype of the system we want to build. The skeleton system will be built using simulation and with limited simplified functionalities to illustrate to show how the system can address the distinct use cases and scenarios defined within the Project by the pilots. The skeleton itself will be used as validation of the architecture as well as a framework for the software construction phase i.e. *Engineering Development*, where the developed skeleton (a very import proof point or concept for the stakeholders) will allow the gathering of architecture review comments to capture and agree on any improvement. If there are no significant comments and/or actions the *Engineering Development* can really start.

3.3 Engineering Development

The *Engineering Development* process is focused on the developing all the software components and/or functionalities described during the *Architecture Design* process. The initial background and baseline are represented by the skeleton developed for evaluating the architecture design. In Circular TwAIn we decided to adopt agile software development processes for rapid and continuous delivery of software functionalities. Specifically, the Feature-Driven Development [6] (FDD) process is used (see Figure 3-6) where the whole software development process is organized around making progress on features.

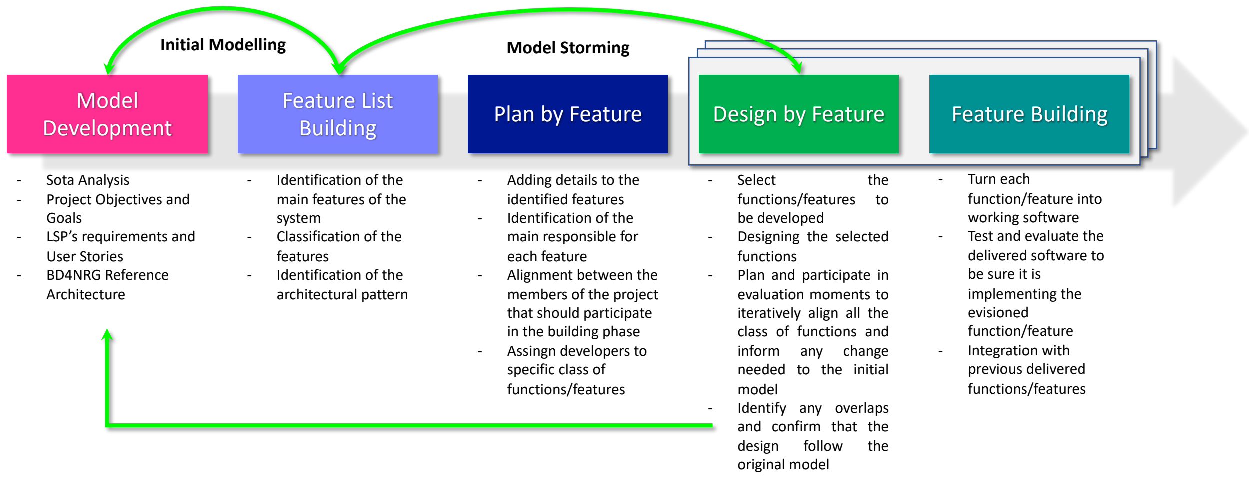


Figure 3-6. Applied software development process: Feature-Driven Development (FDD)

The FDD has been designed by Jeff De Luca and is a model-driven short-iteration process that consists of five main activities, namely:

1. Model Development: the FDD projects starts with the definition of a high-level walkthrough of the scope of the system and its context. Here the architecture description together with the skeleton of the system will drive the development of small models that are part of the overall model that acts as an outline of the system.
2. Feature List Building: by starting from the information gathered and assembled during the previous stage, a list of required features for the system is created and always validated with the relevant stakeholders.
3. Plan by Feature: once the list of features is created during this stage each feature is enriched with more details and a shared plan is created between the members of the Project that should participate in the building phase.

4. Design by Feature: here prioritization rules are applied to the list of features to identify the features that will be technically designed and built.
5. Feature Building: finally, during this stage each feature is turned into working software to be tested, evaluated, and then delivered.

3.4 Wrap-up

In this section the theoretical framework for guiding the design and development of the three types of DTs that the Circular TwAIn Project has been presented. We explained the importance of the planning process where the context of the application is clearly defined by using both State-of-the-Art and stakeholder-driven knowledge together with Project visions and objectives. Further, the way the architecture should be specified, described, and documented is also presented. Specifically, an evolution of the "4+1" view model is described. Finally, since the process needs to be integrated with the software development lifecycle and well-established best practices of software engineering, a description on how this process aligns with the adopted development lifecycle is explained. The Figure 3-7 shows the overall picture of the theoretical framework.

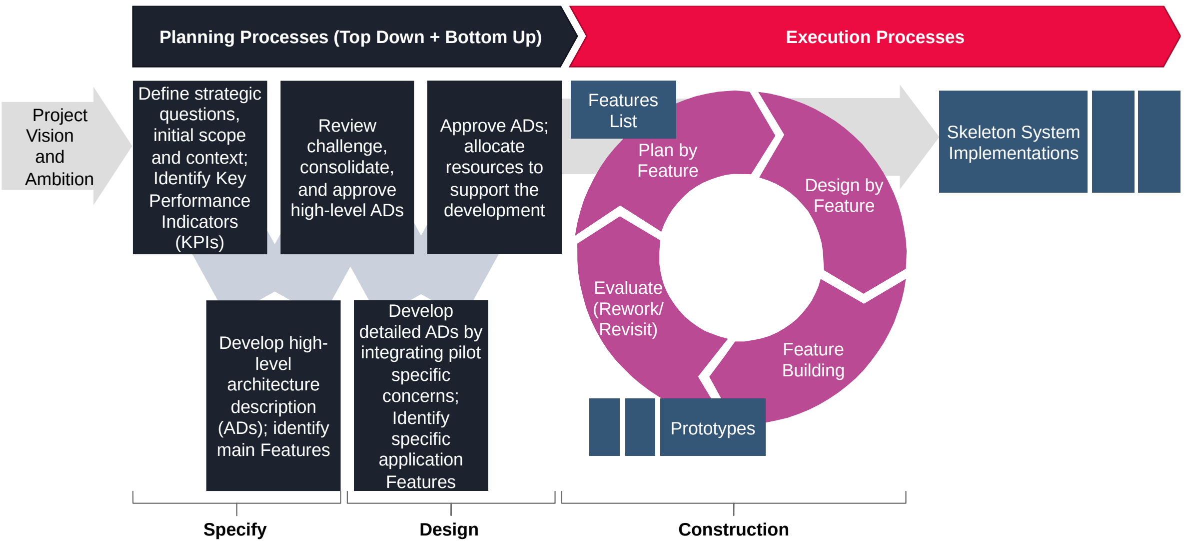


Figure 3-7. Overall representation of the adopted theoretical framework for the design and development of the DTs

3.5 DT Implementation and Design

Implementing a Digital Twin involves careful consideration of various factors and the selection of suitable tools and technologies. By examining the available options and following a systematic approach, we can create effective Digital Twins tailored to their specific needs. Estimations suggest that energy consumption in production can be reduced by 30%-80% using virtual twin technologies [7]. As Digital Twin adoption and intelligent technologies become increasingly pervasive, they will enable better decisions that support a more circular, less carbon-intensive economy, ultimately creating a more sustainable planet. To that end (less "environmentally" costly decisions) the use of ML tools is highly significant. Here, we cite some of the steps and processes involved, while also highlighting key lessons learned from successful Digital Twin implementations.

In Circular TwAIn we try to follow an open-source approach which brings numerous advantages to Digital Twin implementations. Embracing an open-source philosophy allows to leverage community-driven development, flexibility, and cost-effectiveness [8]. Working with various open-source communities and repositories can lead to the discovery of suitable tools and technologies that can be customized and extended to meet specific requirements. Customizability and community support are valuable assets when implementing Digital Twins.

Figure 3-8 below illustrates a DT conceptual model [8] which concept and possible open-source components is provided below.

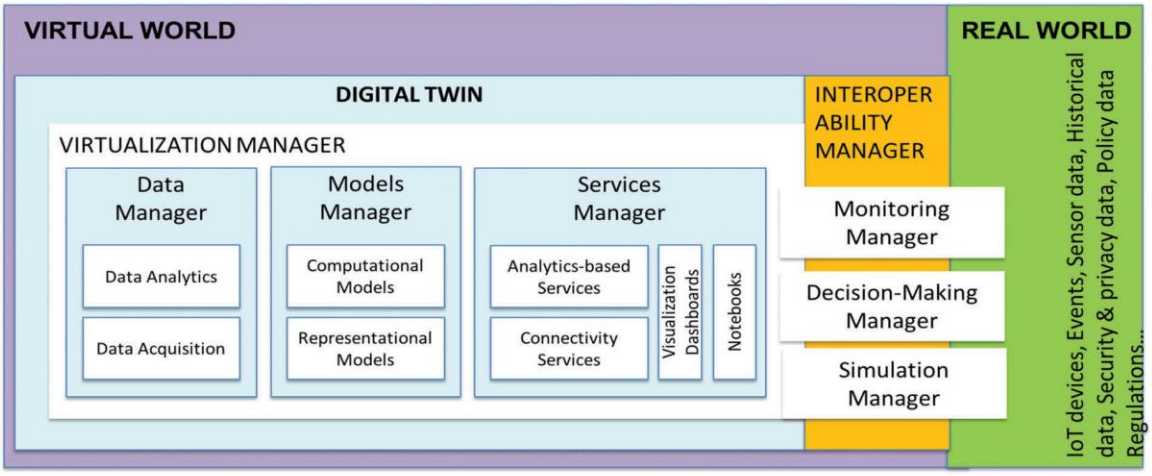


Figure 3-8. Conceptual model of Digital Twin(s) [8]

Data management

One of the critical aspects of Digital Twin implementation is data management. Time-series data plays a crucial role in Digital Twins, and selecting the appropriate database is essential [8]. In DTs, the data acquisition often comprise of real-time sensor data, historical data and inferred data that are generated along the entire product lifecycle and aggregated in big data sets, data integrated from other enterprise systems and third-party systems. Open-source databases like TimescaleDB and InfluxDB offer distinct advantages. TimescaleDB excels in scalability and analytical capabilities, while InfluxDB is designed for high write throughput and efficient disk space usage [9]. Similarly, Apache Cassandra and Elasticsearch are distributed databases suitable for time-series data storage. Cassandra offers exceptional scalability, while Elasticsearch specializes in querying and analysing log data. Carefully considering the specific requirements and characteristics of the data will aid in making an informed choice. The collected data of DTs can be either structured, unstructured or semi-structured. The data should be ingested as a stream in real-time, or as batch-oriented data generated from various sources. The data are often heterogeneous. In DTs, the bigger the diversity of the collected data that the ML model has to analyze and learn about the states that matter along the manufacturing path, the better the model will be. Data representation models are used for storing, exchanging and searching data. Data computation models perform analytics and processing along the product lifecycle phases, supporting, Practically, the collected data should be used to further improve simulation quality and adapt DTs to contextual changes occurring in the system.

Model Manager

Our process is bind to the Model Manager [8]. Model Manager includes Computational Models, which are another vital component of Digital Twins. Open-source frameworks like

PyTorch and TensorFlow provide powerful tools for high-performance computation and machine learning tasks, aligning with D5.1- “Circular TwAIn Data4AI Platform and AI Toolkit”. PyTorch offers dynamic computational graphs that facilitate prototyping and debugging, making it a popular choice among researchers [10], [11]. TensorFlow, on the other hand, is renowned for its distributed computing capabilities and an extensive library of pre-built models [8][9]. Evaluating these frameworks based on factors such as performance, distributed computing capabilities, and development preferences will help in selecting the most suitable option. Diagnostic and predictive analytics focus on using machine learning models and tools to analyse real-time sensor data, diagnose system issues, and predict future behaviour to prevent problems and failures. At the same time prescriptive analytics involves simulating an entire network and using ML optimization techniques to identify optimal solutions that align with circularity of product lifecycle and during all 3 major phases, beginning-of-life (BOL) to middle-of-life (MOL) and end-of-life (EOL) [11], particularly in supply chain planning and scheduling. Both areas heavily involve ML techniques and tools some of which align and identified in D3.3-“Data Space and AI Toolkit Reference Implementations”.

Services Manager

The Services Manager of a DT requires a scalable and modular infrastructure to enable intelligent composition and orchestration of services [8]. To build a scalable and modular architecture for Digital Twins, a microservices approach is often adopted. Microservices architecture involves dividing the Digital Twin into smaller components, each responsible for a specific task [10]. This modularization reduces complexity and allows for easier code maintenance and scalability. Tools like Kubernetes, an open-source container orchestration platform, provide the necessary infrastructure to manage microservices at scale [8]. Additionally, Istio, an open-source service mesh, offers advanced features for managing microservices communication, traffic, and security. By adopting a microservices architecture and utilizing appropriate tools, organizations can create flexible and scalable Digital Twins.

Effective data visualization and analytics play a vital role in deriving insights from Digital Twin data. Tools such as Tableau and Apache Superset provide powerful capabilities for data exploration, visualization, and dashboarding. Tableau, a commercial platform, is renowned for its interactive visualizations and exploration capabilities. On the other hand, Superset, an open-source platform, offers a wide range of data connectors and dashboarding features [9], [10]. Additionally, Kibana, another open-source tool, specializes in log and time-series analytics, while Grafana focuses on visualizing various metrics for performance monitoring and forecasting [8]. The choice of visualization and analytics tools should be based on the specific data sources, analytical requirements, and visualization preferences of the Digital Twin implementation.

Ensuring seamless integration with various devices and data sources is essential for capturing a holistic view of the physical system. To achieve this, open-standard protocols and platforms are utilized. MQTT, a lightweight messaging protocol, is designed specifically for efficient IoT communication and integration. Alternatively, Apache Pulsar, an open-source distributed pub-sub messaging platform, offers horizontal scalability and high performance [9], [12]. Apache Kafka and RabbitMQ are also popular options for integrating multiple data sources and systems. Choosing the appropriate messaging solution depends on the specific requirements of the Digital Twin implementation. To address interoperability issues, it is recommended that these software tools adhere to emerging Industry 4.0 standards, such as the AAS conceptual level and their technological mappings to OPC UA.

Security Considerations

Security is of utmost importance in any Digital Twin implementation and as such clear security measures must be implemented to protect data access and usage. Tools like keycloak or OpenID Connect, an open standard for authentication and authorization, offers a scalable and secure identity solution. Incorporating these security measures into the Digital Twin architecture ensures the confidentiality, integrity, and availability of the data [11].

4 Specifications of the Digital Twins for circularity

4.1 Rationale

The Project will properly structure *Digital Twins for Circular Manufacturing* in order to facilitate their integration and interactions. This will enable collaborative intelligence based on a swarm of Circular Digital Twins to enable AI applications across the entire circular value chain. To this end, Circular TwAIn identifies three highly relevant sources of data and information to train and feed the human-AI applications: (1) the (de-)manufacturing process, (2) the product to be de-manufactured and (3) the human operator. This document will consider three different DTs, namely: process DT, product DT and Human DT.

The Figure 4-1 shows the Circular TwAIn Reference Architecture (RA). It is based on cloud-edge models, and it has been designed to support the design and development of Circular Applications through the defined main actors, namely:

- Seamless Data Sharing between circular actors.
- Collaborative and Explainable AI.
- Digital Twins (Product, Process and Human).

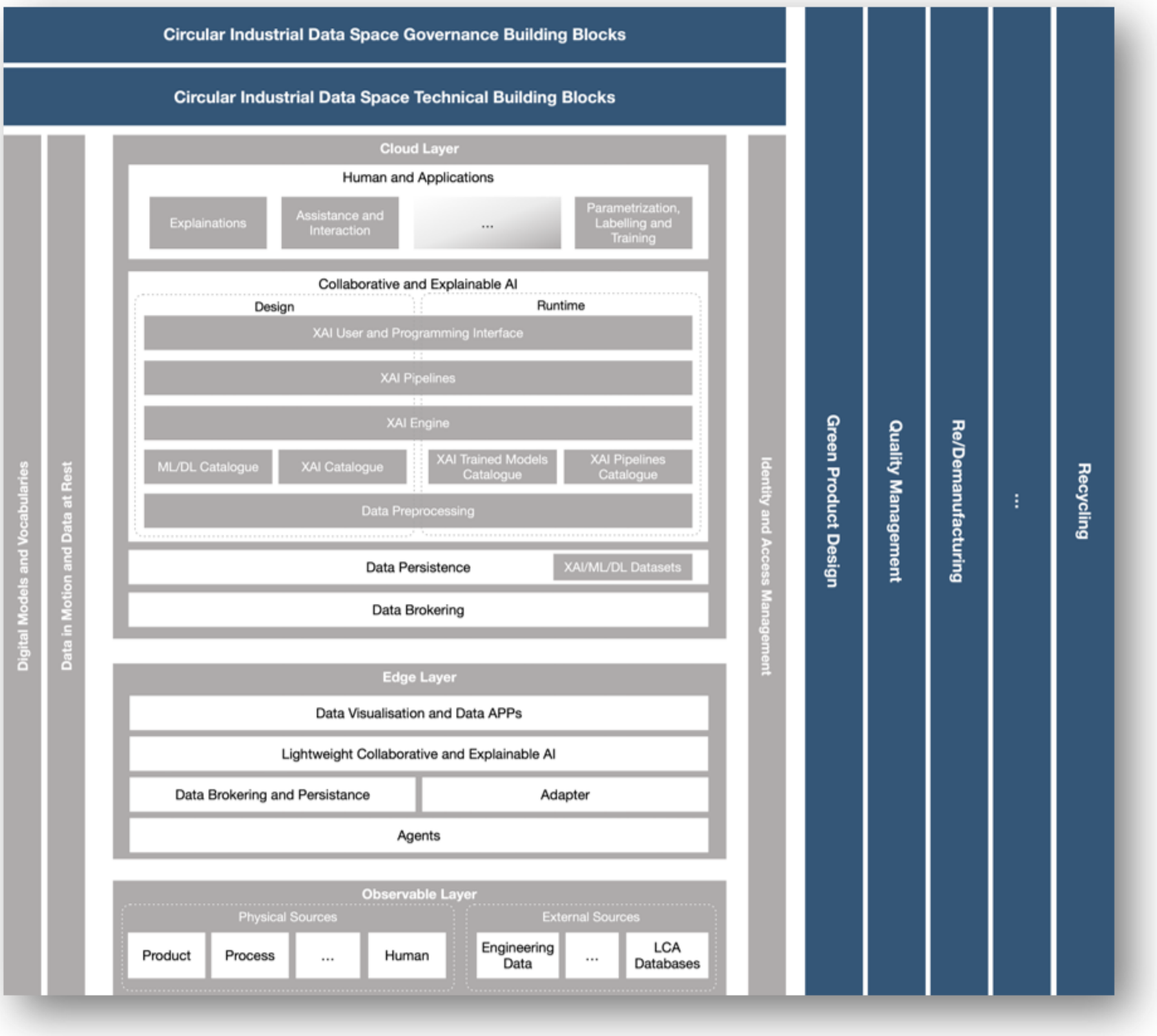


Figure 4-1. Circular TwAIn Reference Architecture (RA) at M9

The objective of the current deliverable is to document the design and development activities around the three distinct DTs that are part of the *Observable Layer* within the Circular TwAIn RA. Due to the complexity of the scenarios within the Project and the high standardization activities and efforts around the DT concept a DT viewpoint has also been developed (see Figure 4-2). According to the figure, in this document the following aspects will be further analysed and developed, namely: the *Data Collection, Provisioning and Modelling Layer*, as well as, *Digital Twin Application Layer*. Concretely, the document will expand some of the blocks within these layers to provide a path that goes from RA to real implementation of the process, product and human DTs. In the following sections (i.e. section 4.2, section 4.3 and section 4.4) the *DT Model and Vocabulary*, *Data Persistence*, *Data Processing* and *Data Ingestion & Brokering* blocks will be refined and aligned with the available technologies and technological stack to be used. Specifically, the following design choice have been taken:

- Process and Product DT: to use the AAS specification and standardized meta-model as the foundation for developing of these DTs. Here open source AAS implementations will be considered and further investigated to include more and more AI.
- Human DT: here the AAS concept does not directly tackle the representation and management of humans, since it primarily focuses on digital representations of machines and assets. However, how to extend AAS with a digital representation of humans is still an open issue, opening to interesting research questions that will be further investigated.

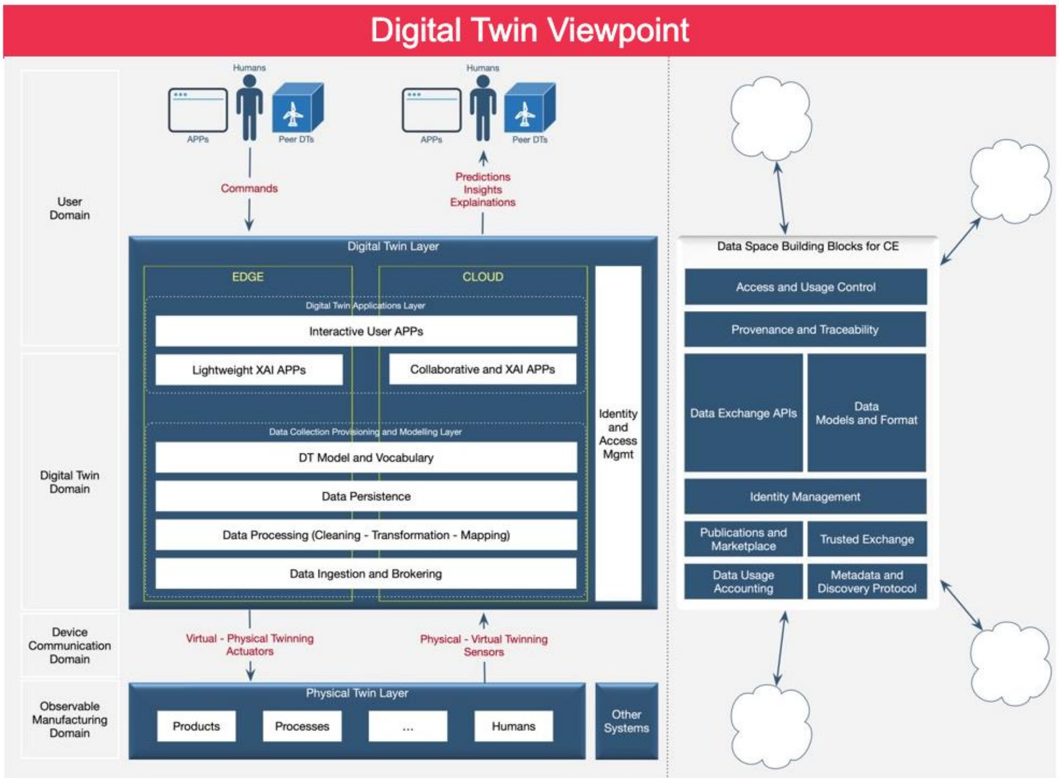


Figure 4-2. Circular TwAIn RA DT Viewpoint at M9

Another aspect is the integration of the DT with the data spaces. Initial plan has already been provided in deliverable D3.2 "Data Space and Digital TwAIns Design - 1st version" related to DT-DS perspective as building blocks but also in deliverable D4.2 "Data Space

Implementations for Materials/Products and Process/Production v1" which is focusing in the DS perspective. So by taking in consideration the Circular TwAIn RA & Building Blocks, the IDSA RA, RAMI4.0 RA and ISO 23247: Digital Twin manufacturing framework (DTMF), which are presented in the deliverable, we are proposing a DT/DS integration which is depicted in Figure 4-3 below.

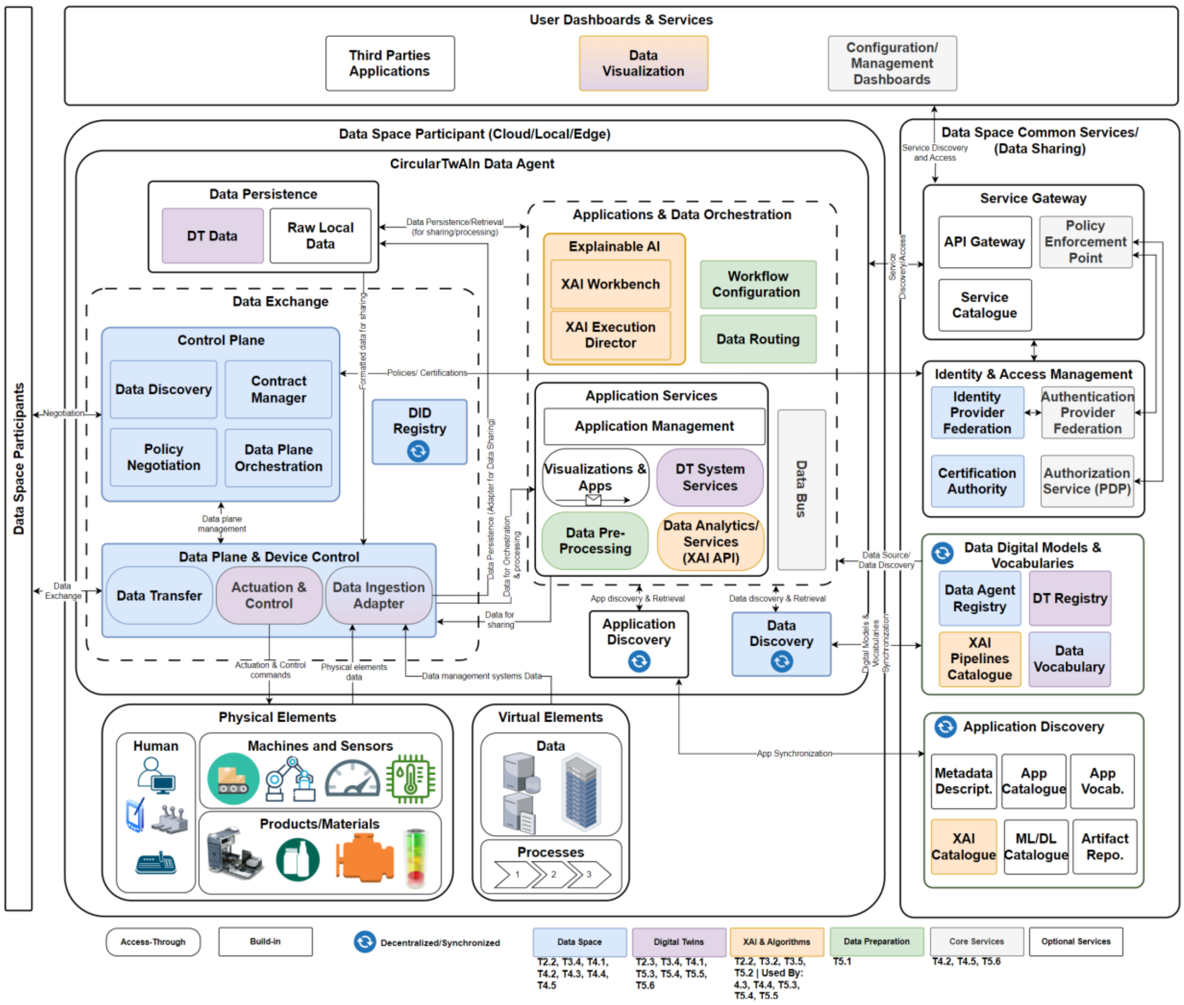


Figure 4-3. Circular TwAIn Functional component diagram.

As we can see in Figure 4-3 above we have instantiated the Circular TwAIn Reference Architecture where the DT components are highlighted with lavender colour. In this functional view we can identify the core DT components like DT registry, DT System, Data collection (Data Ingestion Adapter), DT repositories (DT Data), Visualizations and Data Vocabularies. The DT System Services can encapsulate a complete DT system solution that can interact with the rest of the system thru the DT API.

The Circular TwAIn RA and its DT Viewpoint and the DS integration represents the *Input 0* to the specification of the three DTs.

Finally, since in this document we are interested to identify the main feature of the tree envisioned DTs then the Circular TwAIn Industrial Data Platform (a technology infrastructure based on the Circular TwAIn RA) – fully documented in deliverable D4.1 – Circular TwAIn Data Platform, Standards Ontologies v1 – will be not part of the document. However, the provisioning of the Development, Deployment and Operational Views will requires an deeper analysis and strong integration with the Circular TwAIn Industrial Data Platform since it acts as a man-in-the-middle between DTs and the Data Space itself.

4.1.1 Circular TwAIn Main Scope for Digital Twins

The business activities performed by enterprises in designing, developing, and delivering their product (linear value chain), can potentially be the basis for differentiation and could be optimized for improving sustainability (see Figure 4-4).

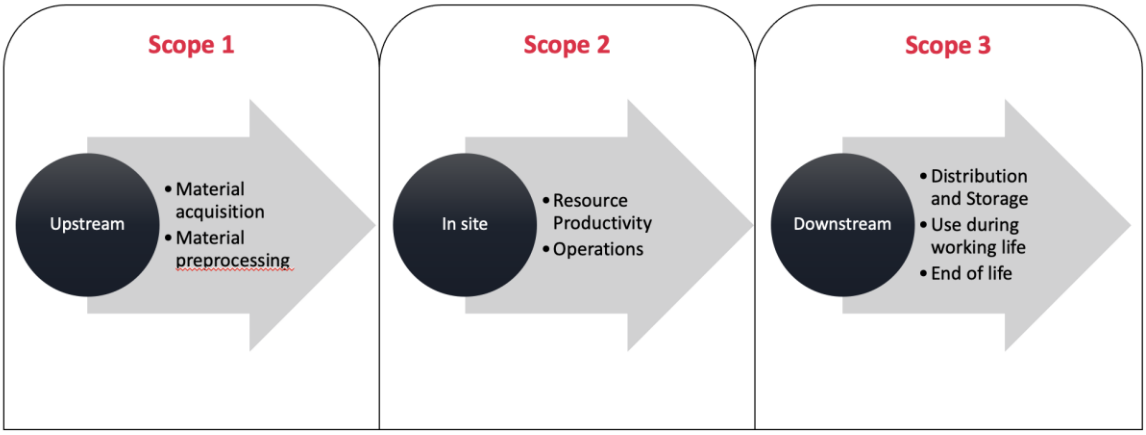


Figure 4-4. The footprint of a product spread across the manufacturing value chain (adapted from [13])

Specifically, circularity can create the foundation for more and more waste reduction, greater resource productivity, reduction of the environmental impact of production activities, etc. The "Supply-Circle" (see Figure 4-5) shows that the resource productivity requires a comprehensive approach that considers the whole supply circle.

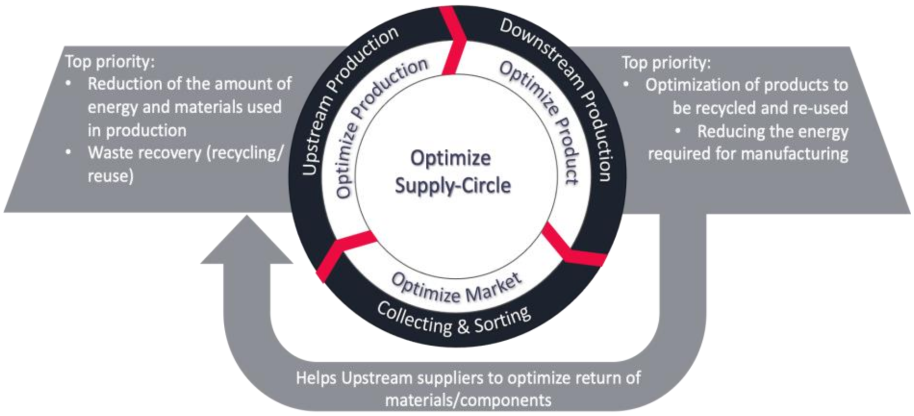


Figure 4-5. "Supply Circle" for exploring opportunities to increase resource productivity [13]

Depending on where they are located on the production circle, companies should prioritize four broad areas for resource productivity: production, product design, value recovery, and supply-circle management.

4.2 Process Digital Twin

4.2.1 Context Viewpoint

Input 0	Circular TwAIn Reference Architecture
Input 1	System Scope
Input 2	State-of-the-Art Analysis
Input 3	Generic KPIs for DT in production process
Input 4	Application specific KPIs in pilots
Output 1	List of Process DT features
Output 2	System Concept
Output 3	Context Diagram

Input 1: System Scope

The process DT will be deployed within an organization and will be responsible to facilitate the movement towards sustainable manufacturing by adopting intelligence and autonomy enabled by the deep use of Artificial Intelligence (AI) techniques.

As stated in [14], there is still much to achieve in reducing the scope 2 emissions. Resource productivity and performance optimization are key elements for reducing the operational costs while establishing greater operation stability and a more responsible usage of resources.

In this landscape, the process DT shall allow companies to focus primarily on activities within their operations where they have the most control. Secondly, by taking advantage from the communication with both material and product DTs, it shall enable companies to turn their attention to the activities that require collaboration between organizations, customers and/or other stakeholders (see Figure 4-6).

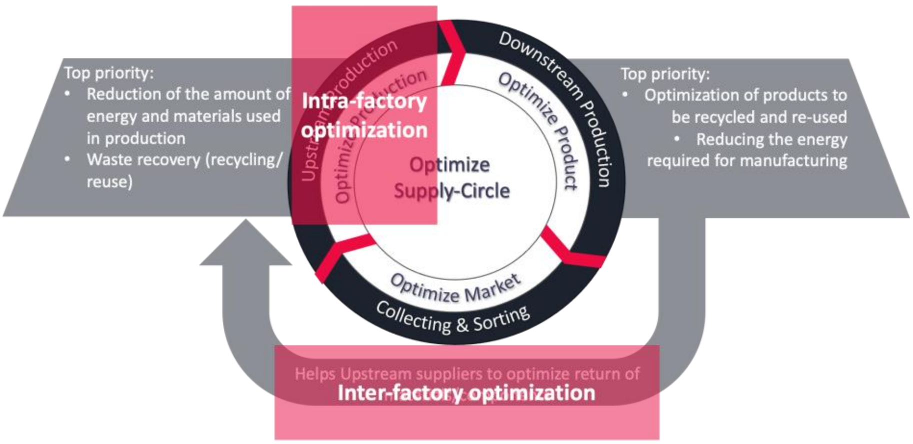


Figure 4-6. “Supply Circle” strategic focus areas for process DT [13]

The development of sustainable and circular production systems requires a systematic approach to the acquisition and development of the necessary capabilities for extracting sustainable-related data, interpret and process this data to compute and monitor Key Performance Indicators (KPIs) and targets to understand the root causes of losses as well as the process inefficiencies. In this scenario, newest tools aided by Artificial Intelligence (AI) are providing the foundations for a better identification and evaluation of the process changes. Here, the adoption of new technologies and approaches – in general – can help manufacturing companies to improve the overall sustainable strategy by including and using circularity data.

Even if the focus of the process DT is on the scope 2, scope 1 and scope 3 can further benefit from the information integration and communication between the three envisioned DTs, namely: process, product/material and human.

The development of strategies for implementing sustainable manufacturing is now a reality and more and more companies are committing themselves to implement more and more climate-friendly actions (see Table 4-1) [15].

Table 4-1: An example of companies that are committed to implement ambitious climate actions

Company Name	Near Term	Long Term	Net-Zero
BMW Group	1.5ºC/Well-below 2ºC		Committed
Continental	1.5ºC		
Faurecia S.A.	1.5ºC		Committed
Gestamp	Well-below 2ºC		
Linde plc	Well-below 2ºC		
Mercedes-Benz AG	1.5ºC/Well-below 2ºC		Committed
Philip Morris International	1.5ºC	1.5ºC	2040
Robert Bosch GmbH	1.5ºC		Committed
Royal Philips	1.5ºC		
…	…	…	…

Input 2: Backgrounds and State of the Art (Applying the Top-Down Approach)

Digital Twin (DT) is a quite old term, it was firstly adopted in 1991 by David Gelernter in his book Mirror Worlds. The concept has been further developed by Grieves that used it as a conceptual model for enabling the Product Lifecycle Management (PLM) [16], [17]. In 2010, the term DT was firstly used by John Vickers - a NASA's leading manufacturing expert and manager of NASA's National Center for Advanced Manufacturing – and essentially connected to simulation [18]. A DT can be defined as the virtual representation of a physical asset – physical product, system and/or process. A DT is made up of three fundamental elements, namely[1]:

1. a real space containing a physical asset;
2. a virtual space containing a virtual asset; and

[1] *Design, Modeling and Implementation of Digital Twins*

3. a link for data flow from the real space to the virtual space and information flow from the virtual space to the real space.

Therefore, a DT can be seen as a digital representation of a physical asset and its process.

Since in Circular TwAIn a strong alignment with the Reference Architecture Model for Industrie 4.0 (RAMI4.0) is required, then the concept of Asset Administration Shell (AAS) is adopted for defining a DT. The AAS is a key concept in RAMI4.0 and it is used to provide a data image of an asset, or in other words, to describe electronically an asset in a standardized manner so that data can be exchanged smoothly between assets and production orchestration systems, engineering tools, and/or any software that need to manage a production system. Saying that, in a “harmonized” production system, i.e. a production system populated by AASs, a process DT or *cognitive DT*[2] can be defined as a “higher level” AAS that once set up and operational it is asked for continuously monitoring and actively optimizing the process by collecting data through the orchestration of the AASs available within the data space for processes. Furthermore, it is also required to interact with the product and human DT developed in tasks 5.3 and 5.5. Considering this, next sections will be dedicated to further explain the proposed concept for the process DT.

2

RELEVANT RESEARCH PROJECTS/INITIATIVES FOR BUILDING UP THE SPECIFICATION

EUROPEAN RESEARCH PROJECTS

The Table 4-2 provides a list of relevant European research projects where the concept of Digital Twin has been deeply investigated, studied, and showcased in typical manufacturing scenarios (e.g., quality, sustainability, lifecycle assessment activities, etc.). This list assembles the overall knowledge of the Research and Technological Development (RTD) partners of the Circular TwAIn Project in designing and developing DT-based solutions for manufacturing and represents the foundation for the design and development of DTs strongly focused on AI and circularity.

Table 4-2. European Research projects related to Process DT

Project Name	Project Details	Involved Partners
AI-REGIO	https://www.airegio-project.eu	POLIMI, NISSATECH, ENG, SUITE5, TECNALIA, ENGINEERING
CANVAAS	https://www.eitmanufacturing.eu/news-events/activities/connected-assets-interoperability-framework-via-aas/	POLIMI
CAPRI	https://www.capri-project.com	CORE, AIMEN, NISSATECH, POLIMI, ENGINEERING
COGNITWIN	https://www.sintef.no/projectweb/cognitwin/	FHG IOSB, NISSATECH , TEKNOPAR, SINTEF
CHANGE2TWIN	https://www.change2twin.eu	
DIGI-PRIME	https://www.digiprime.eu	COBAT, TECNALIA, POLIMI, NETCOMPANY
DIMOFAC	https://dimofac.eu	NETCOMPANY, AIMEN, POLIMI, TECNALIA
KYKLOS4.0	https://kyklos40project.eu	NETCOMPANY, TECNALIA, GFT
PROASENSE	https://cordis.europa.eu/project/id/612329	NOVA, NISSATECH
PROPHESY	https://prophesy.eu	NOVA, NETCOMPANY
QU4LITY	https://qu4lity-project.eu	NOVA, ENGINEERING, POLIMI, NETCOMPANY

THE GLOBAL LIGHTHOUSE NETWORK

The Global Lighthouse Network (GLN) is a community of manufacturers that are committed in heavily using and deeply exploring the Fourth Industrial Revolution (4IR) technologies to transform factories, value chains and business models [19]. It encompasses a diverse range of manufacturing contexts across varied industries [20]. The study points at four “durable shifts”, namely: agility and customer centricity, supply chain resilience, speed and productivity, and eco-efficiency. The members demonstrate how to use 4IR technologies to engage the durable shifts in the context of the four walls of the individual sites as well as end-to-end across the value chain. The study includes now 90 members of which three are designed as sustainability lighthouse, i.e., adopting the 4IR technologies and approaches for achieving a step-change levels of environmental impact. According to the GLN research, 4IR-driven transformation is the trigger for strong operational performance improvements and – consequently – better sustainability and environmental impact reduction.

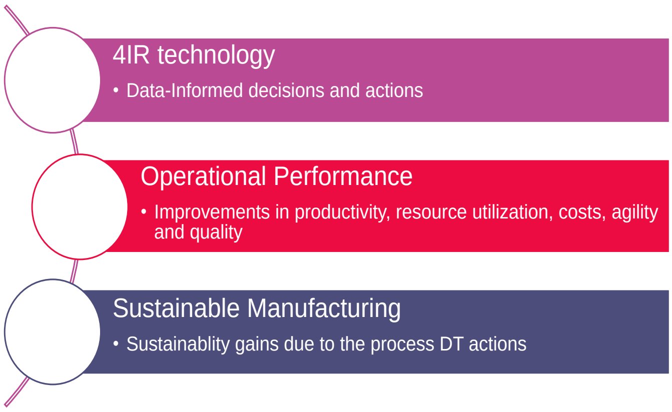


Figure 4-7: Sustainable Manufacturing as the result of the usage of 4IR technologies

This is exactly where the developed process DT will play a fundamental role: using data and AI tools to enable data-informed actions across the production line, while using relevant circular information (such as product/material DT) to increase the operational performance of the system.

INDUSTRIAL INITIATIVES AND STANDARDS

REFERENCE ARCHITECTURAL MODEL FOR INDUSTRIE 4.0: HIERARCHY LEVELS

The RAMI4.0 explains the hierarchical organization of manufacturing enterprise using the standards IEC62264 and IEC61512. According to these standards, a manufacturing enterprise is typically organized into 4 levels structured using the functional and physical hierarchy as shown in Figure 4-8.

The hierarchies depicted in the figure allows to clearly identify the boundaries and the define the scope and range of the component we are going to design and develop. Concretely the process DT will be designed to support both manufacturing operations and manufacturing execution systems. Here hyper connectivity, communication standardization and normalization as well as easy orchestration of event-driven systems play a key role.

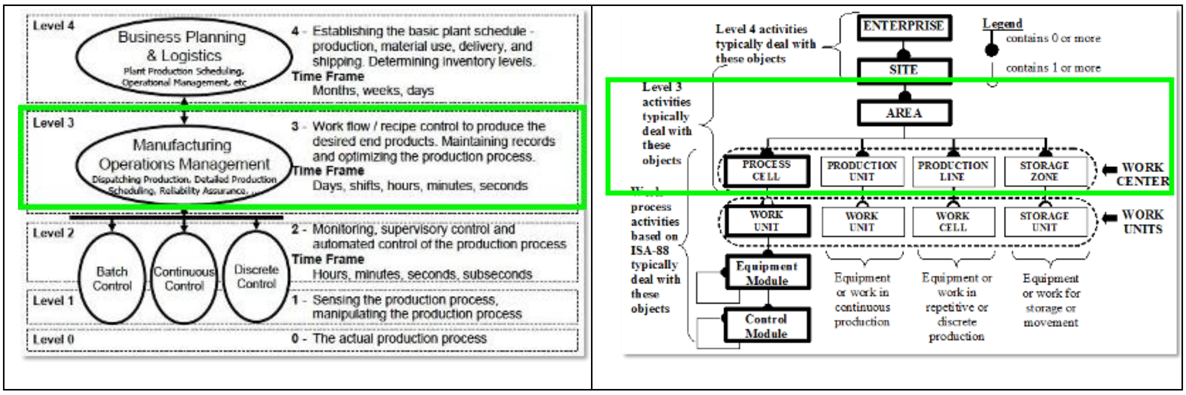


Figure 4-8. ANSI ISA-95 and ISA 88 functional and physical hierarchies of a manufacturing enterprise

REFERENCE ARCHITECTURAL MODEL FOR INDUSTRIE 4.0: THE ASSET ADMINISTRATION SHELL

The successful implementation of Industry 4.0 solutions in practice strictly depends on the presence of standards. Standardization allows Industry4.0 systems to retain their stability, i.e. the use of Industrie 4.0 solutions requires interoperability so that components, devices, and applications can communicate seamlessly across companies, industries and countries. In this scenario, the concept of I4.0 component and of the Asset Administration Shell (AAS) take a fundamental role (see Figure 4-9). I4.0 components are globally and uniquely identifiable elements of an I4.0 system capable to communicate by offering services. The basic idea behind I4.0 components is to wrap each asset with an "administration shell" or AAS that is responsible to deliver a minimal, and above all, standardized digital description of a physical asset (data image). The Reference Architecture Model for Industrie 4.0 (RAMI4.0) is building the whole digital transformation strategy on the top of the AAS concept, representing a standardized digital representation of the asset, corner stone of the interoperability between the applications managing the manufacturing systems.

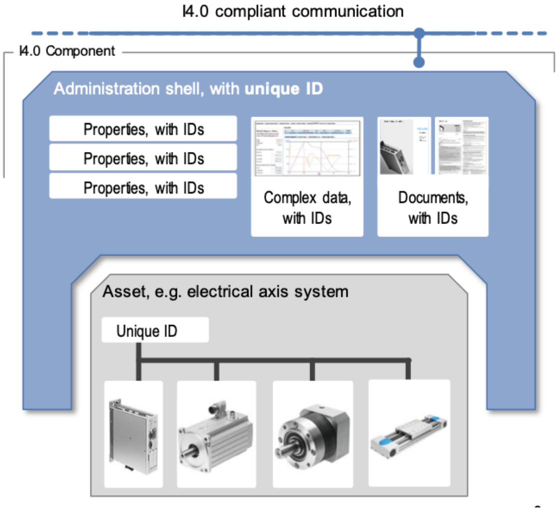


Figure 4-9. Asset Administration Shell Representation [21]

The key features of the AAS are:

1. Allows the integration of both non-intelligent and intelligent products in and Industry 4.0 solutions.
2. Supports the complete lifecycle of products, devices, machines and facilities.
3. Allows for integrated value chains.
4. Provides the basic infrastructure for the development of autonomous and AI systems.

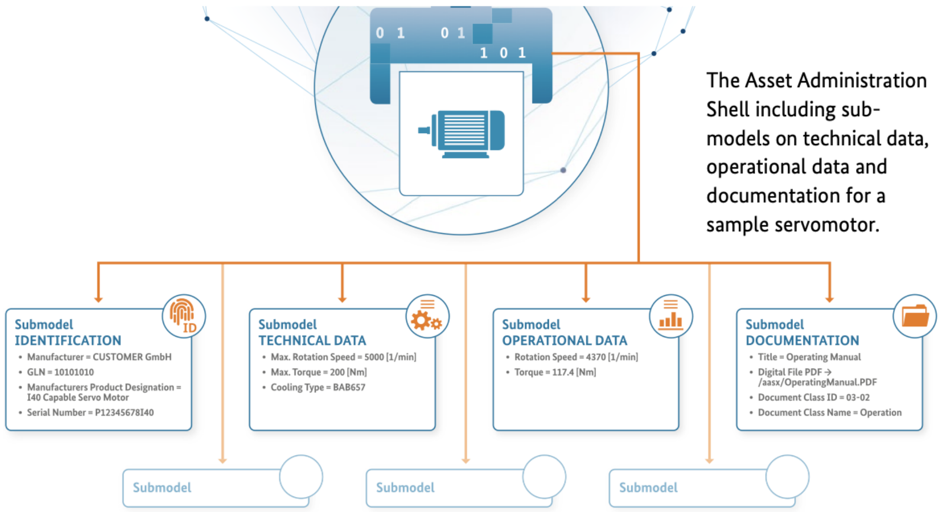


Figure 4-10. Asset Administration Shell Structure and submodels composition [22]

In the Industrie 4.0 world, each asset is represented by an AAS – its own "Internet presence" or "I4.0 Digital Twin" – the contains/includes the digital description of the asset in terms in terms of submodels and properties (see Figure 4-10).

The AAS provides the basis and conceptual foundations for the developing the process DT.

INDUSTRIAL INTERNET CONSORTIUM REFERENCE ARCHITECTURE

Functional Viewpoint

The *functional viewpoint* is an architecture viewpoint that frames the functional capabilities, structure, and connections of an IIoT system. In the context of the process DT the viewpoints that are relevant are:

1. Application Domain: relates with the functions that implement application logic for specific business functionalities. Therefore, this domain comprises rules, models, engines, activity flows, etc. that implement specific functionalities that are required for the use case under consideration. These functionalities are typically exposed by using Application Programming Interfaces (APIs) and User Interfaces for enabling the human interactions with the application.
2. Business Domain: relates with business functions that an IIoT system must integrate for supporting business processes, i.e. to enable the integration and compatibility between the IIoT system functions and enterprise business systems such as Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Product Lifecycle Management (PLM), Manufacturing Execution System (MES), asset management, service lifecycle management, etc.

Implementation Viewpoint

The implementation viewpoint is one of the most interesting aspects of the Industrial Internet Reference Architecture (IIRA) especially when compared to other industrial initiatives such as RAMI4.0. It is a very technological viewpoint where different architectural patterns for IIoT systems are presented and explained. As stated in [23], architecture patterns represent some common, typical and essential features of IIoT systems implementations that are easy to recognize and understand by practitioners. They are examples and references for conceptualizing real world IIoT systems architectures, and architects may derive final architectures that may substantially be different from them. Three architectural patterns have been considered and explained for designing and developing IIRA compliant software systems, namely:

- three-tier architecture pattern: comprises edge, platform, and enterprise tiers. The edge tier collects data from the edge nodes connect using proximity network. The platform tier receives, processes and analyses data flows from the edge tiers and other tiers. Furthermore, it processes and forwards commands from the enterprise tier to the edge tier. It provides functions for managing devices. The enterprise tier implements domain-specific applications, decision support systems and provides interfaces to end-users. Finally, tiers are connected through different network types. The *proximity network* is the one that connects sensors, actuators, devices, control systems and physical assets (in one word edge nodes). These nodes are then connected to gateway devices that bridges other networks. The *access network* allows the connectivity between the edge and platform tiers, i.e., allows the data and control flows between the two tiers. It could be a corporate network, an overlay private network over the public internet or a 4G/5G network. The *service network* ensures the connectivity between the services within the platform and enterprise tiers. It may be an overlay private network over the public Internet or the Internet itself, allowing the enterprise grade of security between end-users and various services.

- gateway-mediated edge connectivity and management architecture pattern: comprises a local connectivity solution for the edge of an IIoT system with a gateway that, in turn, bridges to a wide area network. By using this pattern, it is possible to localize operations and controls while breaking down the complexity of IIoT systems. This pattern is suitable for stable clusters of resources within the local network boundaries.
- layered databus architecture pattern: provides low-latency, secure, peer-to-peer data communications across logical layers of the system. It is most useful for systems that must manage direct interactions between applications in the field, such as control, local monitoring, and edge analytics. At the lowest level, smart machines use databuses for local control, automation, and real-time analytics. Higher-level systems use another databus for supervisory control and monitoring. Federating these systems into a System-of-Systems (SoS) enables complex, Internet-scale, potentially-cloud-based, control, monitoring and analytic applications. A databus is a logical connected spaces for applications and services where interoperability is guaranteed by a set of common schemas shared by the endpoints. Since each layer of the databus can implement its own data model adapters and translators are required to connect the layers.

These patterns are extremely interesting in Circular TwAIn to draw, design and develop the hierarchies and the communications between the process DTs, the product/material DT and the human DT, as well as, to explain their interactions with the legacy systems.

ISO 30141 – Internet Of Things Reference Architecture /ISO 23247 – Digital Twin Framework for Manufacturing

The Digital Twin framework for manufacturing is a set of protocols for making and maintaining Digital Twins. The ISO 23247 describes a Digital Twinning system using a layered architecture pattern (see Figure 4-11). The lowest layer describes the observable manufacturing elements. This layer describes the items on the manufacturing floor that need to be modeled. Officially it is not part of the framework because it already exists. The second layer is the device communication entity. This layer collates all the state changes of the observable manufacturing elements, and sends control programs to those elements when adjustments become necessary.

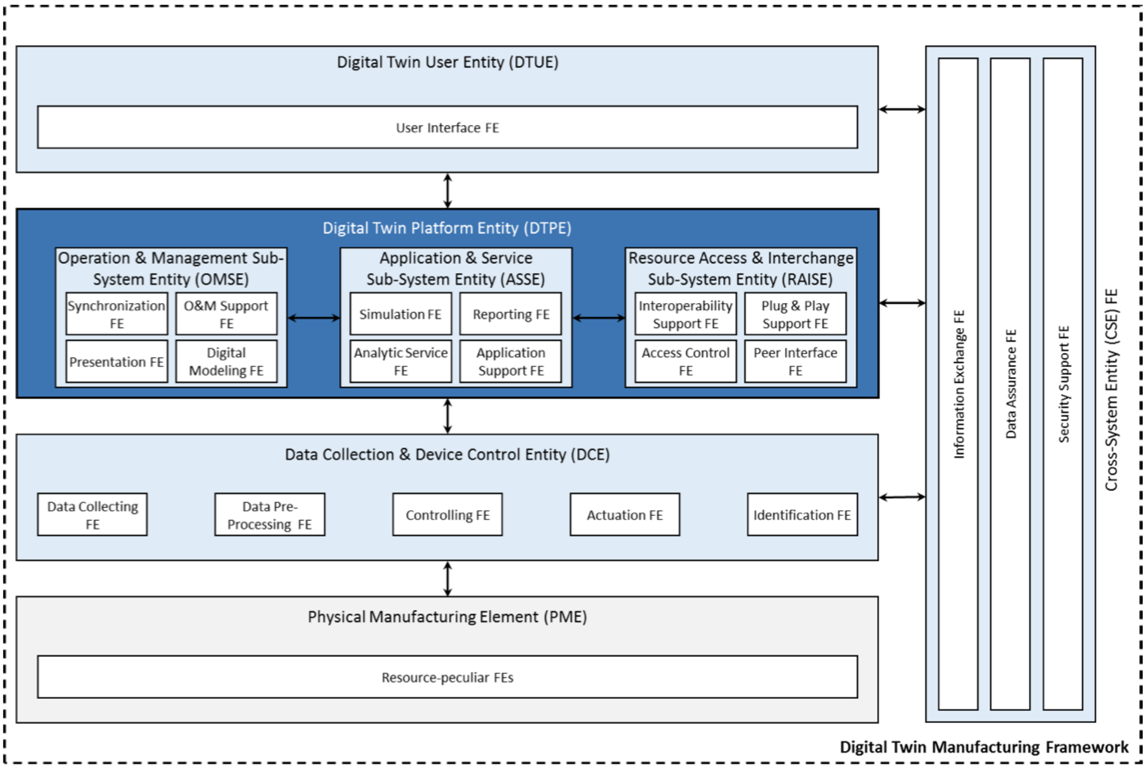


Figure 4-11. ISO 23247 Digital Twin Manufacturing Framework Reference Architecture

The third layer is the Digital Twin entity. This layer models the Digital Twins. It reads the data collated by the device communication entity and uses the information to update its internal models. The fourth layer contains user entities that includes any application (both legacy and non-legacy) that wants/needs to use data from the Digital Twin to improve the production process. The ISO 23247 framework is based on the Internet of Things. The functional entities of ISO 30141 are customized for manufacturing.

Input 3: Process DT Generic KPIs Analysis

Generic KPIs

The first step in system specification is the definition of the functional model of the Process DT. The functional model describes firstly the domain, the objective, and the functional requirements for the DT. In particular, the domain and the objective are necessary to specify the context in which the DT will operate and its role. As the result of this preliminary analysis there are a set of relevant Key Performance Indicators (KPIs) to be considered for process optimization in circular manufacturing. The Table 4-3, shows a list of high level KPIs for production and consumption.

Table 4-3. Preliminary List of relevant generic KPIs for process DT

Area	ID	Indicator	Enabler
Production and Consumption	G_KPI1	Improve resource consumption to production ratio	Availability of an infrastructure to support the uptake of process optimization
	G_KPI2	Inventory Reduction	
	G_KPI3	Change-over Shortening	
	G_KPI4	Increase productivity through the exploitation of the digital platform	
	G_KPI5	Involve end-users in the design process of sustainable products	Availability of an infrastructure for engaging costumers and wider stakeholders (data space)
	G_KPI6	Increase energy Savings	Availability of an infrastructure to support the uptake of process optimization
	G_KPI7	Total increase in value added	i) Availability of an infrastructure to support the uptake of process optimization ii) Availability of an infrastructure for engaging costumers and wider stakeholders (data space)
	G_KPI8	Reduction of disassembly time	i) Availability of an infrastructure to support the uptake of process optimization ii) Availability of an infrastructure for engaging costumers and wider stakeholders (data space)
	G_KPI9	Keeping products/processes in use longer	Availability of an infrastructure to support the uptake of process optimization
	G_KPI10	Making more efficient use of processes (including OEE)	
	G_KPI11	Total energy use, including operational energy	
	G_KPI12	Product Cost Reduction	i) Availability of an infrastructure to support the uptake of process optimization ii) Availability of an infrastructure for engaging costumers and wider stakeholders (data space)
	G_KPI13	Quality cost Reduction	Availability of an infrastructure to support the uptake of process optimization
	G_KPI14	Operating Cost Reduction	

Matching Generic and Specific KPIs

Table 4-4. Matching Generic KPIs with specific KPIs (taken from pilot's handbooks) for Process DT

Area	ID	Indicator	WEEE	BATTERIES	PETROL	Enabler	Remarks
Production and Consumption	G_KPI1	Improve resource consumption to production ratio	KPI1, KPI2	KPI5	KPI1	Availability of an infrastructure to support the uptake of process optimization.	This process specific KPIs can be satisfied using both only data related to the process and product data such product usage as well as product manufacturing data.
	G_KPI2	Inventory Reduction		KPI3, KPI5			
	G_KPI3	Change-over Shortening		KPI1, KPI2			
	G_KPI4	Increase productivity through the exploitation of the digital platform	KPI2, KPI3, KPI4	KPI1, KPI2, KPI4	KPI3		
	G_KPI5	Involve end-users in the design process of sustainable products				Availability of an infrastructure for engaging costumers and wider stakeholders (data space)	Data should be shared between different actors and stakeholders for designing better processes and tools. Moreover, information about product usage can be used for shifting from a take-make-dispose to a circular model. Therefore, sharing schemas are then needed.
	G_KPI6	Increase energy Savings			KPI1, KPI3	Availability of an infrastructure to support the uptake of process optimization	This improvement does not have direct impact on circular economy.
	G_KPI7	Total increase in value added	KPI1	KPI5		i) Availability of an infrastructure to support the uptake of process optimization. ii) Availability of an infrastructure for	Any improvement in process operation can have impact the in the overall final value. Furthermore, the integration of data shared schemas by using the data space can have impact on the process itself and bring to new improvements.

						engaging costumers and wider stakeholders (data space)	
	G_KPI8	Reduction of disassembly time	KPI3	KPI1, KPI2		i) Availability of an infrastructure to support the uptake of process optimization ii) Availability of an infrastructure for engaging costumers and wider stakeholders (data space)	This is possible by using automating operations and tasks during the disassembly. A more accurate plan for disassembly can be obtained if product life-cycle data can be used.
	G_KPI9	Keeping products/processes in use longer	KPI1, KPI4			Availability of an infrastructure to support the uptake of process optimization	Better process operations and tasks together with better characterization lead to improvements in product time of life and the establishment of a circular economy.
	G_KPI10	Making more efficient use of processes (including OEE)	KPI2, KPI3, KPI4		KPI1, KPI2, KPI3		This improvement does not have direct impact on circular economy.
	G_KPI11	Total energy use, including operational energy			KPI1		This improvement does not have impact on circular economy.
	G_KPI12	Product Cost Reduction	KPI2, KPI3, KPI4	KPI3, KPI5		i) Availability of an infrastructure to support the uptake of process optimization ii) Availability of an infrastructure for engaging costumers and wider stakeholders (data space)	Production costs can be reduced as result of process optimizations as well as integration of information between the different stakeholders in a circular business model (increased material/component reuse, less problems during disassembly operations, etc)

	G_KPI13	Quality cost Reduction	KPI2, KPI4	KPI2, KPI3		Availability of an infrastructure to support the uptake of process optimization	Improvements in process operations and related activities can have impact on the final product quality. Moreover, in circular economy the determination and the assessment of the quality of the product is critical and requires information sharing between the different stakeholders.
	G_KPI14	Operating Cost Reduction	KPI2, KPI3, KPI4	KPI1, KPI2, KPI3, KPI4	KPI1, KPi2, KPi3		This improvement does not have direct impact on circular economy.

Input 4: Pilot Trials Handbooks (Applying the Bottom-up Approach): Process DT Application Specific KPIs

Circular TwAIn Use Cases: gathered from the Pilot Handbooks

BATTERY		
Digital Assembly and Machines		
UC. A	Computer-vision driven collaborative robotics for the disassembly of LIB packs	KPI1, KPI4, KPI8, KPI10, KPI12, KPI14
UC. B	Machine learning aided automated disassembly of LIB modules	KPI1, KPI4, KPI6, KPI8, KPI9, KPI10
Digital Quality Management		
UC. C	AI tool for the characterization of the LIBs state-of-health combining historical and testing data	KPI3, KPI9, KPI10, KPI13
Digital Maintenance		
UC. D	AI tool for optimized mechanical recycling of degraded LIBs	KPI1, KPI2, KPI14

WEEE		
Digital Assembly and Machines		
UC. A	Computer-vision driven product identification for the disassembly of IT equipment	KPI3, KPI4, KPI14
UC. C	Real time planning of the disassembling operations	KPI1, KPI2, KPI3, KPI12
UC. D	Collaborative Robotics for the support of manual operations	KPI1, KPI4, KPI8, KPI10, KPI12
Digital Performance Management		
UC. B	Characterization and assessment of components and subcomponents	KPI3, KPI9, KPI10, KPI12, KPI13

PETROLCHEMICAL		
Digital Performance Management		
UC. A	Data acquisition and representation for AI framework designer	KPI4
UC. B	Developing a hybrid circular twin of the process	KPI4
UC. C	Use of data analytics, AI, and model verification to understand process unit failures	KPI4, KPI9, KPI14
UC. D	Developing AutoML module for Process Industry	KPI4, KPI9, KPI10, KPI14
UC. E	Generation of a tool for process optimization	KPI4, KPI9, KPI10, KPI14

Output 1: List of Process DT Features

Considering both generic and specific KPIs lists, the following features (see Table 4-5) can be derived for the process DT (at the current status of the Project and considering the pilot specificities, ALL, WEEE, BATT and PETROL).

▶ : Ongoing feature development

■ : Planned but not started feature development

Table 4-5: List of required features for the Process DT

Id	State	Description
PDT_F_ALL_1	▶	Implementing features to create and initialize Digital Twins of physical assets and processes
PDT_F_ALL_2	▶	Dynamic data collection and extraction from different data sources at pilot's system
PDT_F_ALL_3	▶	Capture and monitor real-time data from sensors and IoT devices attached to physical assets. This includes tracking parameters like temperature, humidity, pressure, energy consumption, as well as, visual inspection systems, robot operations, etc.
PDT_F_ALL_4	▶	Process and/or pre-process data extracted from at pilot's system
PDT_F_ALL_5	▶	Support the execution of AI models both embedded and as a service
PDT_F_WEEE_BATT_6	▶	Use computer-vision algorithms for product classification and dynamic planning of disassembly operations
PDT_F_PETROL_7	▶	Use ML algorithms for processing time-series data extracted from the process during the operation
PDT_F_ALL_8	▶	Synchronous and asynchronous event-based communication channels
PDT_F_ALL_9	▶	Data representation and harmonization using the AAS standard
PDT_F_ALL_10	■	Interact with external systems such as Human Digital Twin, Product Digital Twin, AASs, XAI and Data Space components
PDT_F_ALL_11	▶	Provide easy-to-use and model-based orchestration mechanisms based on well-known standards and methodologies such as Finite State Machines (FSM), Business Process Model and Notation (BPMN), State Charts, etc.
PDT_F_ALL_12	■	Designing features that support the remanufacturing process, including identifying components suitable for reuse, managing refurbishment workflows, and tracking

		the quality and condition of remanufactured products. Here the interaction with Product DT will be fundamental
PDT_F_ALL_13		Building features that facilitate collaboration and communication among stakeholders involved in the circular manufacturing process. This can include sharing information, exchanging insights, and coordinating activities between designers, manufacturers, suppliers, and customers
PDT_F_ALL_14		To include analytics capabilities to measure and assess the environmental and economic impacts of circular manufacturing practices in selected processes. This involves assessing resource consumption, waste generation, and carbon footprint, and generating meaningful reports and insights

Output 2: System Concept

The process DT will be deployed within an organization and will be responsible to facilitate the movement towards sustainable manufacturing by adopting intelligence and autonomy enabled by the deep use of Artificial Intelligence (AI) techniques.

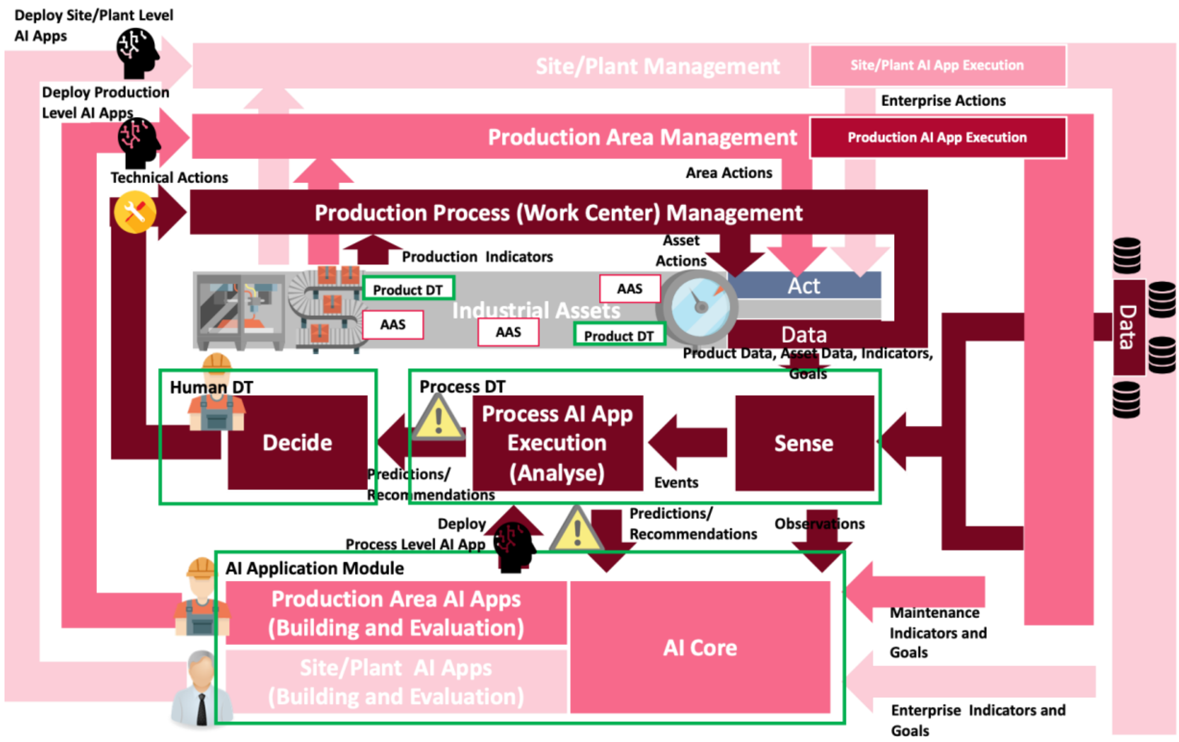


Figure 4-12. Scope of the process DT (internal to the manufacturing company)

The Figure 4-12 shows the role of the process DT, it shall comprise a set of tools, components and/or capabilities that all together will enable the data collection from a range of AASs and other DTs for improving resource productivity.

Finally, the Figure 4-13 shows how data space modules can be used to share data between the different actors in circular economy. The approach presented is inspired to, however, more details about the specification of data space for circularity and implementation details are presented in the deliverable D4.2 – Data Space Implementations for Materials/Products and Process/Production 1st version.

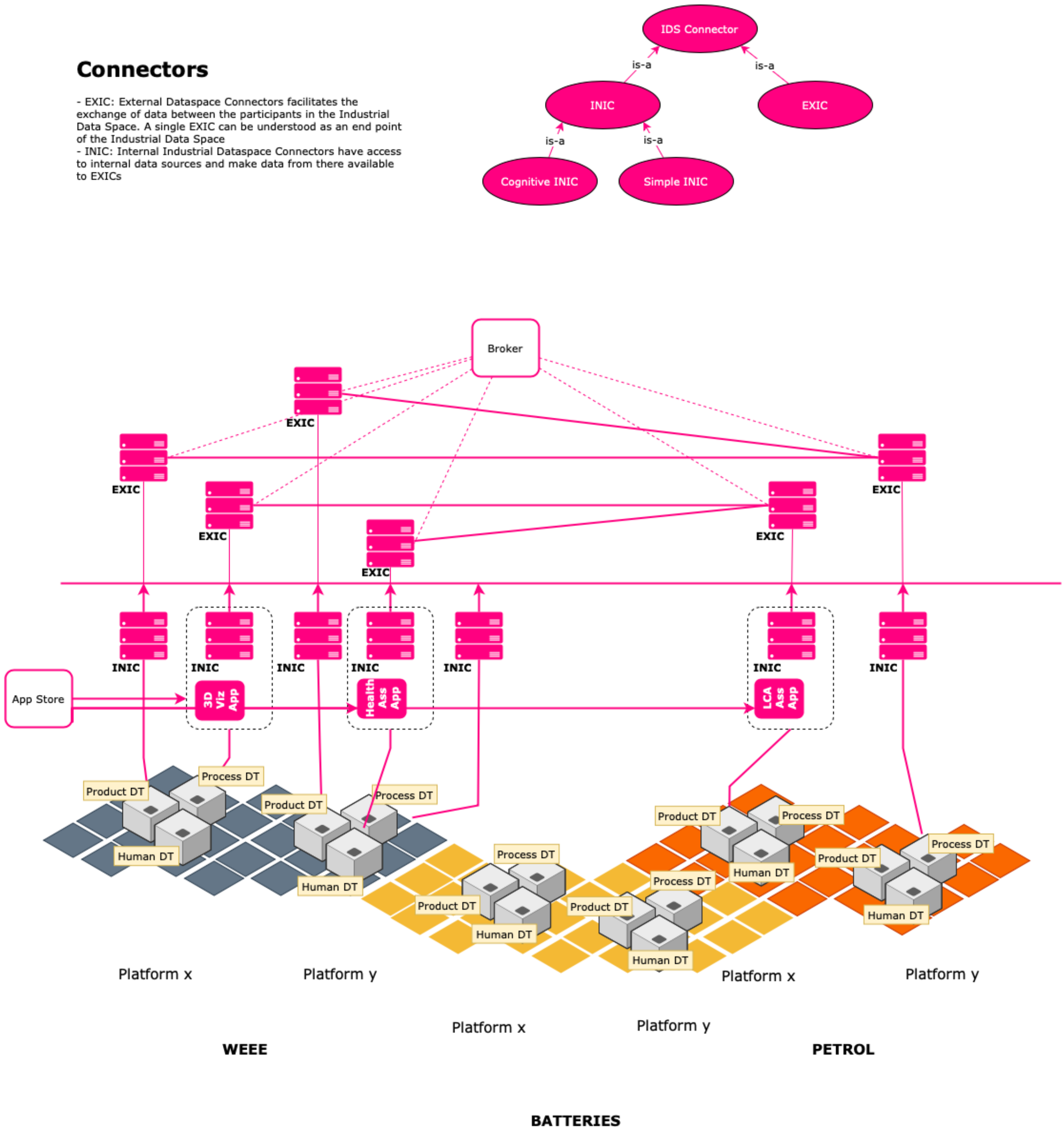


Figure 4-13. Data Space concept for the three considered pilots

Output 3: Context Diagram

In the Figure 4-14, the context diagram of the process DT is presented. The importance of the context diagram is considerable since it displays and resumes in one figure all the interactions with the system under study. In this case, the process DT is seen as a black box, this means that no information related to the internal structure and/or component composition and expected functionalities is presented. Thus, the diagram strictly consists of three main entities, namely: 1) External entities; 2) Interactions; and 3) the system under study.

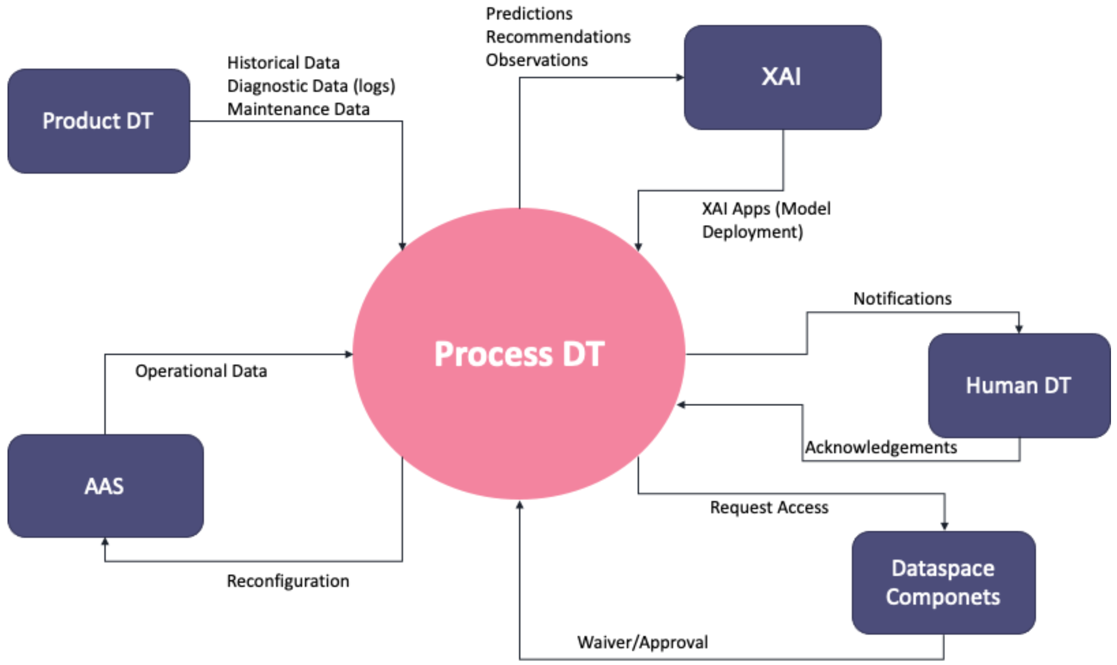


Figure 4-14. Preliminary Context Diagram for the process DT

4.2.2 Functional Viewpoint

Logical Level Design

The Figure 4-15 shows the preliminary architecture of the Process DT. The main assumption is:

The Process DT is a virtual representation of a process that incorporates real-time data together with other forms of AI to analyze the system behavior, performance, and outcomes. Therefore, the process DT can be seen as a higher-level AI-enabled AAS that ingests from AASs deployed in the production line and other DTs (product and person/human). This "newer" AAS is called cognitive AAS and will be especially designed to collect, preprocess data and execute AI/ML models for computing answers, insights, optimizations, while solving "circular manufacturing" problems.

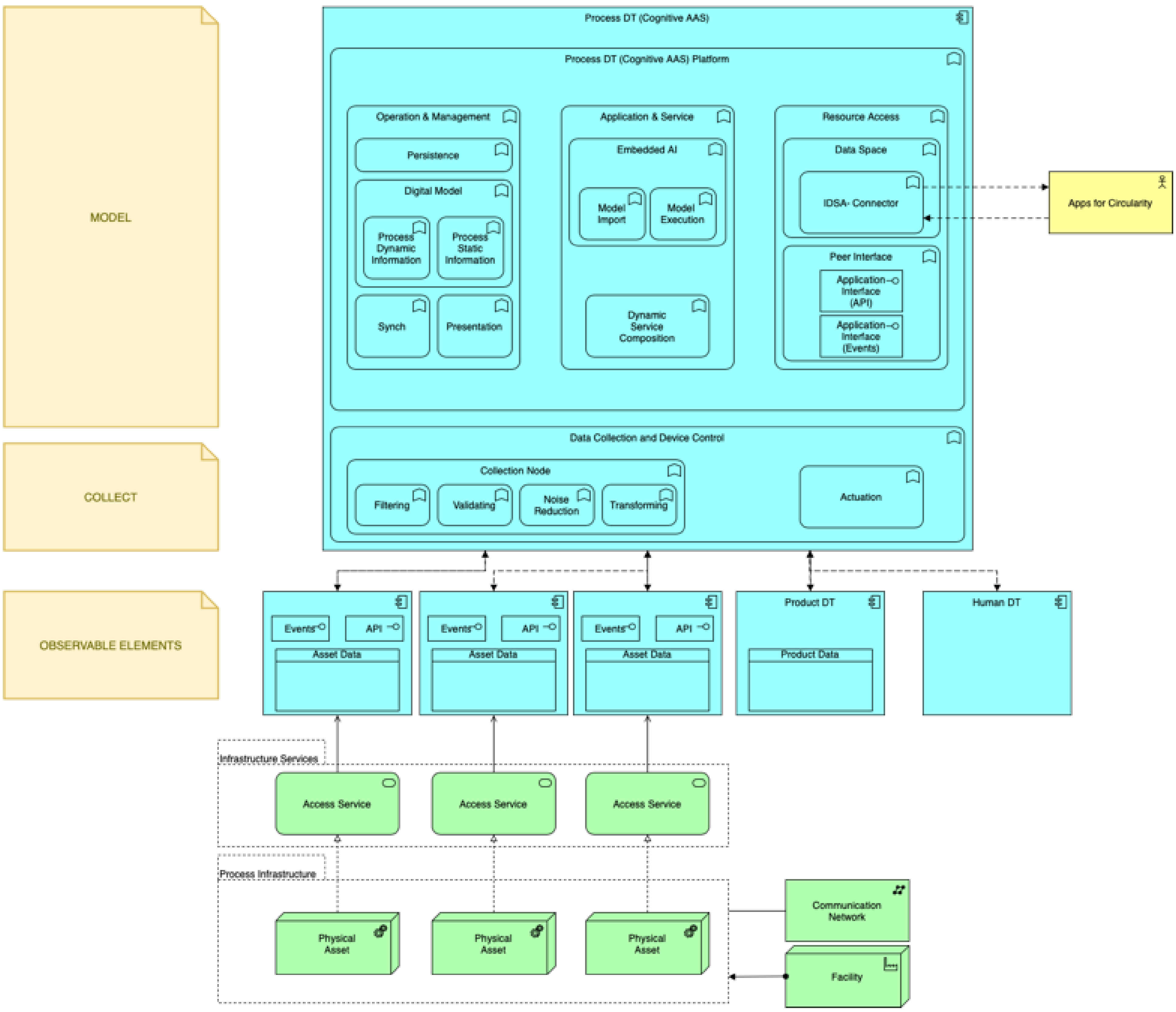
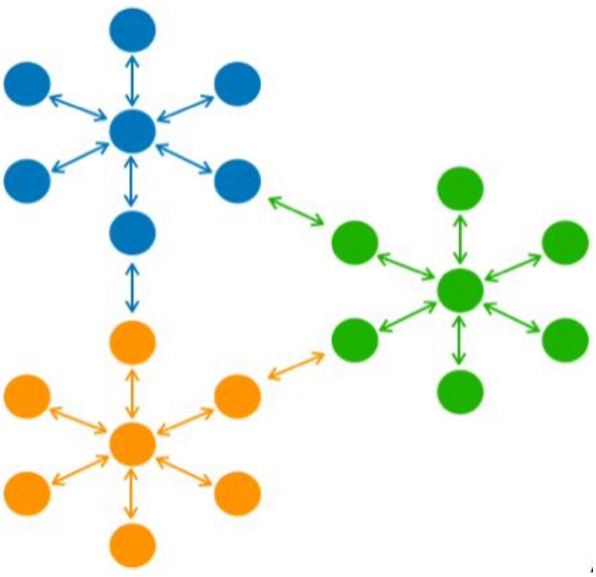


Figure 4-15. Preliminary Architecture of the Process

Subsystems and Components

Subsystem	
Name	Process DT
Interfaces	- REST API - MQTT Event-based communication
External Entities	- AAS deployed in the production line - Product DT - Human DT - Circular Apps (using Data space connectors)
Processes/Responsibilities	Especially designed to collect, preprocess data, and execute AI/ML models for computing answers and solving "circular manufacturing" problems.
Notes	The internal structure of the Process DT is aligned with the Digital Twin manufacturing framework (ISO 23247) that provides an overview of Digital Twin manufacturing and describes general principles as well as its internal structure.

Component	
Name	Collection Node
Component/Responsibilities	The component is responsible to connect the process DT to the system and collect and preprocess data from heterogenous resources. The preprocess task will include filtering, validation, quality checks as well as the transformation of the data into a format that can be easily synchronized with the digital model. The component can be replicated to handle data and events according to the specific domain, namely: process units, product DT, human DT. Domain specific events or data can be then further aggregated and preprocessed to feed the embedded AI component. 

Component	
Name	Actuation
Component/Responsibilities	The component is responsible to send commands back to the environment.

Component	
Name	Digital Model
Component/Responsibilities	The component is responsible for handling the digital representation of the Observable manufacturing element. It contains the description of the capabilities of the process DT in terms of submodels and submodel elements.

Component	
Name	Synch
Component/Responsibilities	The component is responsible to connect and synchronize the collected data with the defined digital model. Specifically, synchronization will be focused on dynamic properties within the domain model (properties that are related with the observed manufacturing elements and are changing over the time).

Component	
Name	Persistence
Component/Responsibilities	The component is responsible to persist the digital model as soon as something change.

Component	
Name	Presentation
Component/Responsibilities	The component is responsible to provide relevant information about the status of the process DT. Concretely, the component will show the current digital model loaded, the connection status with the other observable units, the possibility to plot time series, opened event channels, etc.

Component	
Name	Embedded-AI
Component/Responsibilities	The component is a core element of the process DT and is responsible to use AI and machine learning techniques to perform advanced analytics. Specifically, the component will execute AI models to provide valuable insights, predictions, and recommendations to the decision makers. The component requires an AI/ML framework like TensorFlow to execute AI models.

Component	
Name	Dynamic Service Composition

Component/Responsibilities	The component is responsible to dynamically connect the deployed collection nodes in order to create higher level aggregated events that are used as input of the embedded AI component.

Component	
Name	Peer Interface
Component/Responsibilities	The component is responsible for managing the peer communication. This means the communication between the process DT and the other observable elements such as product DT, human DT or any other deployed AAS. This component provides then a special channels for intra DTs communication.

Component	
Name	IDSA-Connector
Component/Responsibilities	The component is responsible to enable the creation of digital platform across the value chain. A data space for process will be specifically developed to share data between all the actors of the value chain. Focusing on the process the Data Space will enable to exchange the event data for E2E use cases. Thus, the component will allow the process DT to be part of the Data Space.

4.2.3 Process Viewpoint

The process DT combines the push/pull-based approaches. In particular, it provides a request-reply data exchange pattern to provide data to a *requester* through the standardized AAS REST API over HTTP. Even if the request-reply message exchange pattern can be used to implement both synchronous and asynchronous communication, for the process DT this pattern is implemented in a purely synchronous fashion. As for asynchronous communication, the event-based communication is used to push sensed data outside the DT. In an event-based communication the most important element is the *event* that wraps facts and/or commands and is created whenever a change within the observed entity happens. The design pattern that is used to implement the event-based communication is the *Publish/Subscribe* pattern (see Figure 4-16).

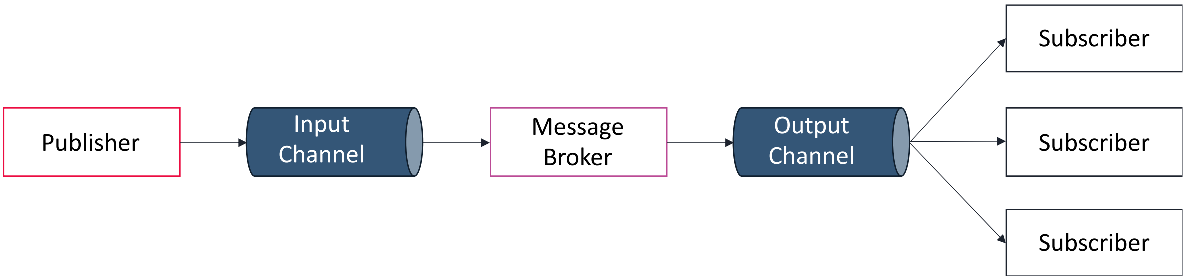


Figure 4-16. Publish/Subscribe pattern

A *Publisher* could be a sensor, monitoring system, a middleware etc. However, as shown in section 4.2.1 (see Figure 4-14) possible *Publishers* and *Subscribers* are AAS, Human Digital Twin, Product Digital Twin, Explainable AI, and Data Space components.

Events are a very versatile mechanism of the AAS. Within the metamodel a *SubmodelElement Event* has been introduced that can used to declare events of an AAS as well as to define the scope of the event. The general format of the *Event* has been already specified in the AAS documentation where several types of events have been identified. However, in the context of the process DT the events related with the *Updates of Properties and dependent attribute* are considered for the 1st version of the component. There are some relevant events related with the *Structural changes of the AAS* as well as *Infrastructure Events* that could be included in future releases to automatize certain tasks in the direction of the Continuous Integration / Continuous Delivery (CI/CD) approach. Saying that, the possible event scope is shown in Table 4-6.

Table 4-6. Considered Event Scopes

Event Attached to…	Scope
Asset Administration Shell	This event is monitoring/ representing all logical elements of an Administration Shell, such as *AssetAdministrationShell*, *AssetInformation*, Submodels.
Submodel	This event is monitoring/ representing all logical elements of the respective Submodel and all logical dependents
SubmodelElementList, SubmodelElemenetCollection Entity	This event is monitoring/ representing all logical elements of the respective SubmodelElementCollection, SubmodelElementList or Entity and all logical dependents (value or statement resp.)
SubmodelElement (others)	This event is monitoring/ representing a single atomic SubmodelElement, e.g., a data element which might include the contents of a Blob or File

Finally, the current structure of the *Event* object is presented in Table 4-7.

Table 4-7. Attributes of the *Event* object

Class:	**Event**			
Explanation	Defines the necessary information of an event instance sent out or received			
Attribute	**Explanation**	**Type**	**Kind**	**Card**
Source	Reference to the source of the Event Element, including identification of AAS, Submodel, SubmodelElements	Reference	Attr	1
sourceSemanticId	semanticId of the source Event Element, if available	Reference	Attr	0..1
observbableReference	Reference to the referable, which defines the scope of the event	Reference	Attr	1
Topic	Information for the outer message infrastructure	String	Attr	0..1
Timestamp	Timestamp in UTC, when this event was triggered	String	Attr	1
Payload	Event specific payload	String	Attr	0..1

4.2.4 Information Viewpoint

For developing the process DT we are deciding to use the AAS as backbone to take advantage from the standardization the REST API, event-based communication and data representation. The AAS's information model can be used to exchange complete Asset Administration Shell via file exchange as well as the basis for exchanging information via standardized API or the event-based communication.

Specifically, the AAS provides a framework and related tools for designing and building data images of an asset. Therefore, by using the metamodel of the AAS the process DT will be capable of processing data, context and observations from other AAS as well as modelling its own data and structuring the observations derived from the processing task. The Figure 4-17 presents an overview of the metamodel of the AAS.

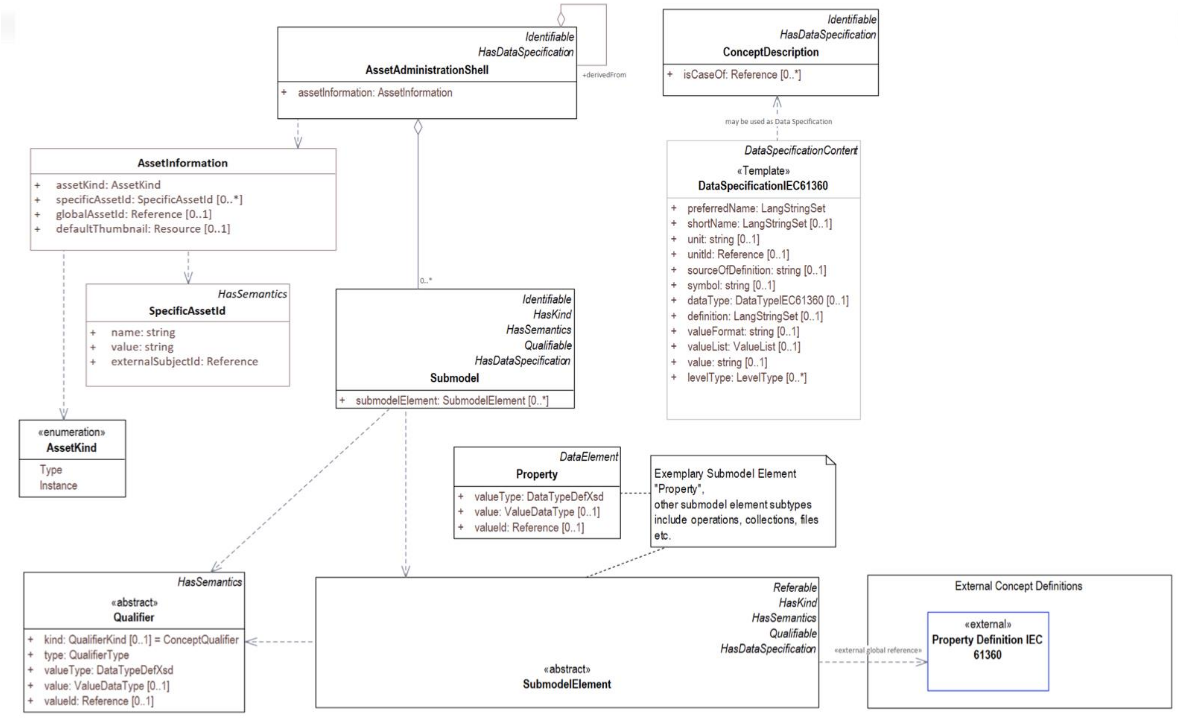


Figure 4-17.Overview of the Metamodel of the AAS

The metamodel of the AAS is fully documented in [24], where all the concepts and relationships between them are deeply explained. In the context of this document the metamodel is only referenced so we suggest to access the [24] for further details.

The Figure 4-18 shows how the metamodel connects to the industrial assets and how the descriptions provided can be connected to external reference ontologies.

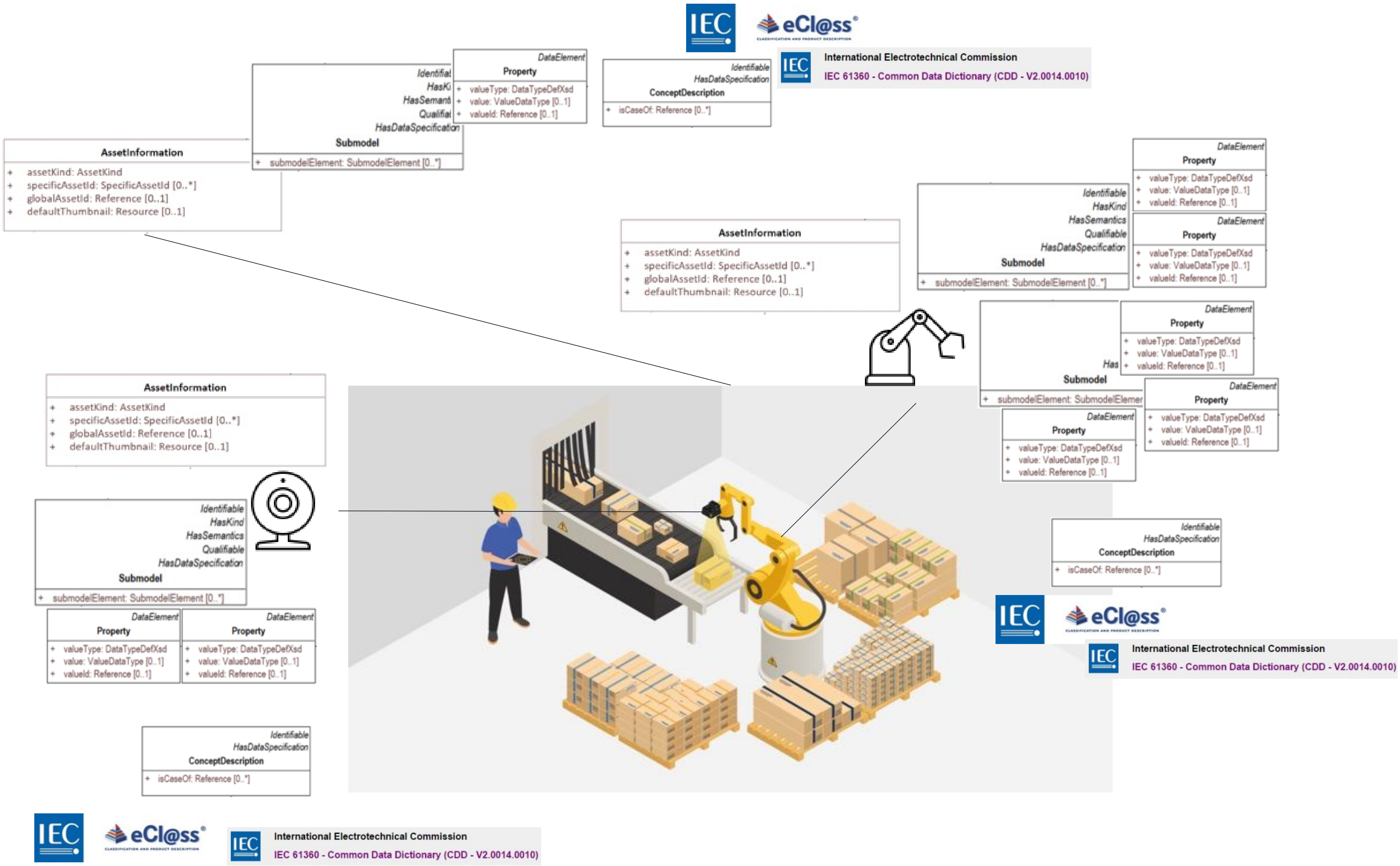


Figure 4-18. Overview on how the metamodel connects to industrial asset and processes.

4.3 Product and Material Digital Twin

When trying to realize a product Digital Twin implementation as already done for the process DT, we should define clear objectives and scope based on the specific use case and goals. Identifying the physical assets or systems that will have Digital Twins and determining the desired outcomes is able to guide the design process and ensure alignment with business objectives. In the case of products/materials DT the steps that should be followed are clearer. It is crucial to continuously monitor and evaluate the Digital Twin product/material, gathering feedback and learning from it to anticipate and predict the state and "behaviour" of its PO counterpart. This iterative approach allows for adaptation and refinement, leading to improved performance and better results [8].The Product DT shares the same "Input 1: System Scope" and "Input 2: Backgrounds and State of the Art (Applying the Top-Down Approach)" as the Process DT provided in 4.2.1 and based on these and on the D3.2 analysis we have decided to use the AAS standard for the product and Material DTs design and implementation. By using the AAS we take advantage the interoperability that it provides using standardized models and interfaces. Additionally it offers numerous instantiations of the AAS submodels and implementations which also strengthens the interoperability perspective by reusing and extending them.

4.3.1 Functional Viewpoint

The Circular TwAIn functional component architecture supporting product and material Digital Twins is depicted in Figure 4-19 below. Each component plays a specific role in the architecture, contributing to the exchange and modelling of product and material data while promoting circular economy practices. This architecture view highlights the DT aspect of the architecture presented in Figure 4-3 above and can be used in three ways.

- as standalone if we would like to use only the DT aspect.
- as a fully integrated version with the Circular TwAIn Data Space features so the one presented in Figure 4-3 is used by merging all of the components of Figure 4-19.
- as a partial integrated version by enabling the DT features of Figure 4-3 by exposing the standardised interface of Figure 4-3 and connecting it thru the "DT System Services" component as part of an application extension.

Let's explore each component of the DT view and its usage in the context of a circular economy domain:

- Data Input layer: represents the physical entities such as products, materials, machines, and sensors but also the virtual elements such as data coming from databased but also from other DT systems such as Process and Human. They provide input data to the system, including information about the condition, usage, and lifecycle of products and materials. This data is crucial for tracking and monitoring the sustainability and circularity of resources.
- Circular TwAIn Product DT Enabler: includes components that enable the creation and management of Digital Twins for products and materials, supporting circular economy scenarios and it includes:
    - Data Collection & Device Control: This component interacts with external data sources and machines to collect data related to product and material attributes, usage, and performance. It facilitates the exchange of information

between physical elements and the Digital Twin system, enabling real-time monitoring and control of resources. It includes the following sub components:

- Data Transfer (Information Exchange): This component handles the transfer of data between different components of the architecture, ensuring seamless communication and information exchange. It enables the exchange and modelling of product and material data across the system, supporting circularity assessments and decision-making processes.
- Actuation & Control: This component enables the system to control and actuate physical elements based on the insights derived from Digital Twins. It allows for optimization of resource utilization, waste reduction, and sustainable production practices in a circular economy context.
- Data Ingestion Adapter: This component adapts and ingests data from various sources, including virtual elements such as databases, into the system. It ensures that relevant data from different sources is properly integrated and available for analysis and modelling.

- Data Persistence: This component is responsible for storing both raw data and Digital Twin-formatted data. It enables long-term data storage, historical analysis, and traceability of product and material information. The stored data can be used for circularity assessments, performance tracking, and decision-making regarding resource optimization.
- Applications & Data Orchestration Group: This group includes components that facilitate the orchestration and analysis of data, supporting circular economy use cases. More specifically this group includes:
  - Workflow Configuration: This component allows users to configure and manage workflows for processing and analysing product and material data. Workflows can be designed to automate circularity assessments, material tracking, and waste management processes.
  - Data Routing: This component routes data to the appropriate destinations within the system. It ensures that data flows smoothly between different components, supporting the exchange and modelling of product and material data for circular economy analysis and decision-making.
  - Data Bus: The data bus facilitates the exchange of data between various components, enabling real-time data sharing and collaboration. It supports the integration of data from different sources and allows for comprehensive modelling and analysis of product and material information in a circular economy context.
  - Application Services: This component provides various applications and services to enhance the functionality of the system. These applications include visualizations, simulation tools, data pre-processing modules, and data analytics capabilities. They enable

users to gain insights into the circularity of products and materials, identify improvement opportunities, and make informed decisions regarding resource management.

- Resource Access & Interchange: This vertical encompasses components that handle resource access and secure data interchange within the system. This vertical includes:
  - Service Gateway: The API gateway and policy enforcement point manage access to system resources and ensure secure communication between different components. It controls the flow of data and enforces policies to protect the integrity and confidentiality of product and material data.
  - Identity & Access Management: This component manages user authentication and authorization. It ensures that only authorized users can access and interact with the system, maintaining the security and privacy of product and material information.
  - Data Digital Models & Vocabularies: This component includes a Digital Twin registry and data vocabularies. It provides standardized models and semantic knowledge for modelling and exchanging product and material data. It enables the consistent representation and interpretation of information, supporting circularity assessments and interoperability.
  - Application Catalogue: The application catalogue manages the registry of applications and artifacts within the system. It allows for easy discovery and integration of third-party applications that enhance the functionality of the architecture. These applications can provide specialized tools for circularity analysis, optimization, and collaboration.
- User Dashboards & Services: This top horizontal layer provides user interfaces and services for interacting with the system. This layer may include:
  - Third-Party Applications: These are external applications integrated into the architecture, offering additional functionalities and services. They can include specialized tools for circular economy analysis, supply chain management, sustainability reporting, etc.
  - Data Visualization: This component presents data in a visually understandable format, providing intuitive dashboards and visualizations. It enables users to explore and analyse product and material data, identifying patterns, trends, and opportunities for circularity improvements.
  - Configuration/Management Dashboards: These dashboards allow users to configure and manage the system, including settings, workflows, data sources, and access controls. They provide a user-friendly interface for system administrators and operators to monitor and control the architecture's behaviour and performance.

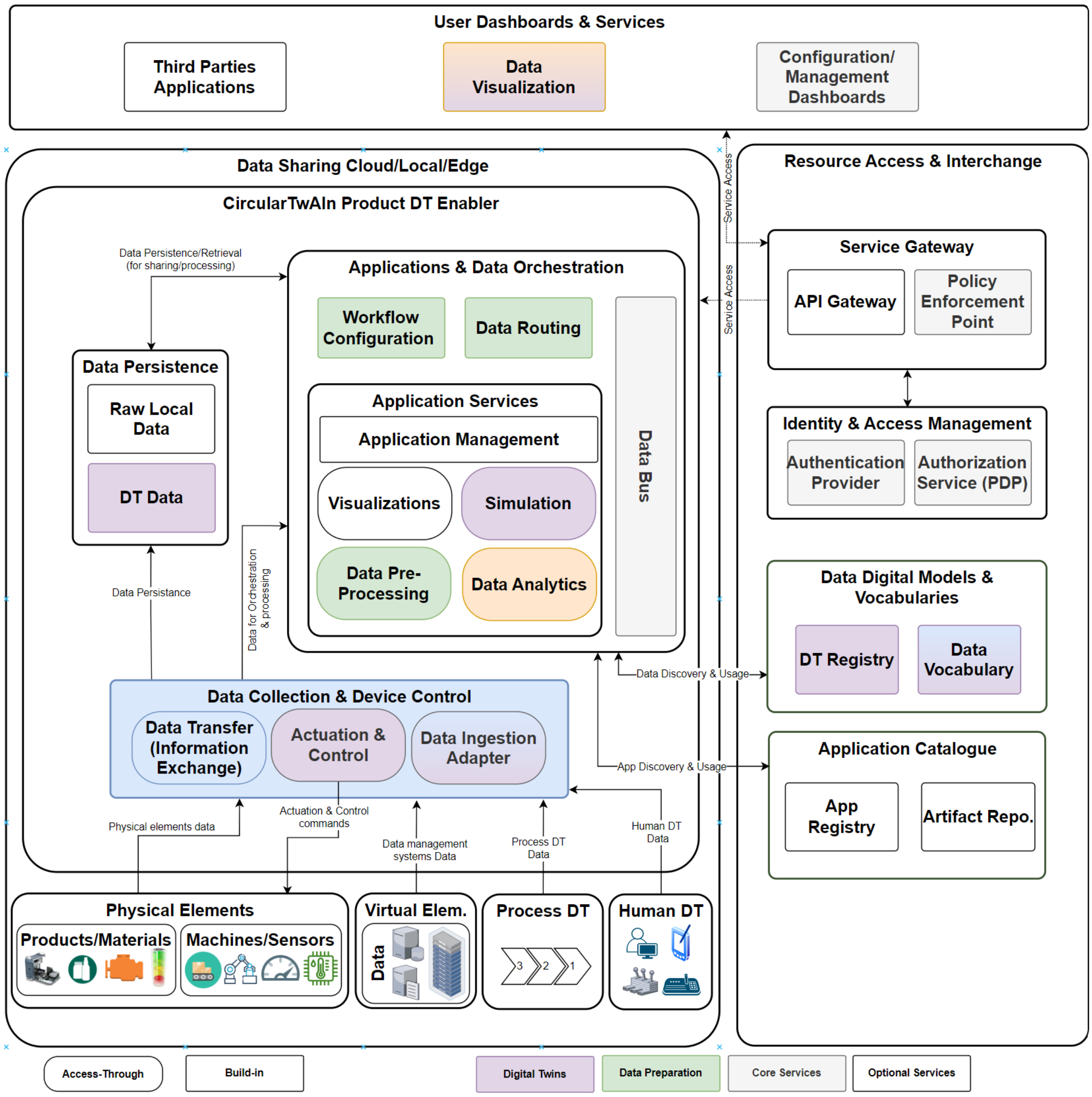


Figure 4-19. Product DT Functional component diagram

The presented architecture supports the creation and management of product and material Digital Twins, facilitating circular economy use cases. It enables the exchange, modelling, and analysis of product and material data to drive sustainability, resource optimization, and waste reduction. By integrating input from physical and virtual elements, as well as human Digital Twins, it provides a comprehensive framework for monitoring and improving the circularity of resources throughout their lifecycle.

4.3.2 Information Viewpoint

As mentioned above based on the SoTA analysis performed for the product/material DT we have decided to use the AAS model and its submodels. Submodels constitute the content of the Asset Administration Shell. They describe content-related or functional aspects of a product. To support an interoperable sub model in Circular TwAIn we have used an existing submodel template from the Industrial Digital Twin Association[3] and more specifically the

[3] https://industrialdigitaltwin.org/

published "Hierarchical Structures enabling Bills of Material" submodel[4] [Industrial Digital Twin Association, 2023]. This submodel template is designed to provide a hierarchical structure for industrial equipment in a way that allows for interoperability. It utilizes Entities and Relationship Elements from the Asset Administration Shell (AAS) Metamodel. Industrial equipment, such as production lines, modules, and subsystems, are supplied by various partners in the value chain, including suppliers, equipment manufacturers, and systems integrators. These equipment are then used by industrial operators and end users in specific applications, both in factory and process automation settings. The equipment can be composed of subsystems, materials, and components, and can be described on both a type and instance level. They may also include information about the produced products.

The AAS incorporates Submodels that cover different aspects of the product throughout their life cycle. During the design phase, products are combined and aggregated into hierarchical structures. Usually, products have their own AAS, referred to as a "SelfManagedEntity," but there are cases where a product does not have its own AAS and is represented by a co-managed entity. Since the AAS metamodel prohibits the nesting of AAS and Submodels, this Submodel Template is intended to describe the internal structure of a product. Its purpose is to allow consumers of an AAS to identify products and their corresponding entities, as well as to locate their respective AAS if they exist. This Submodel acts as an index, pointing to products (described as co-managed or self-managed entities) and AAS within a distributed network that goes beyond the boundaries of a single organization.

Instances of this Submodel Template serve as the authoritative source for hierarchical structures within an AAS throughout all phases of the products' life cycle. It enables the discovery of additional information about each product and its life cycle phase, extending to multiple levels of the hierarchy and across the entire supply chain, depending on the design of the specific Submodel Instance. Based on the above we have concluded that this submodel provides a good match for the representation of the Circular TwAIn products and materials since except its capability to model them it can also identify relationships between them by generating e.g., a product that it may be consisted of multiple other products or materials.

In figure Figure 4-20 below we can find the "Hierarchical Structures enabling Bills of Material" submodel depicted in the AASX package explorer[5].

[4] *IDTA Number: IDTA 02011-1-0*
[5] *https://github.com/admin-shell-io/aasx-package-explorer*

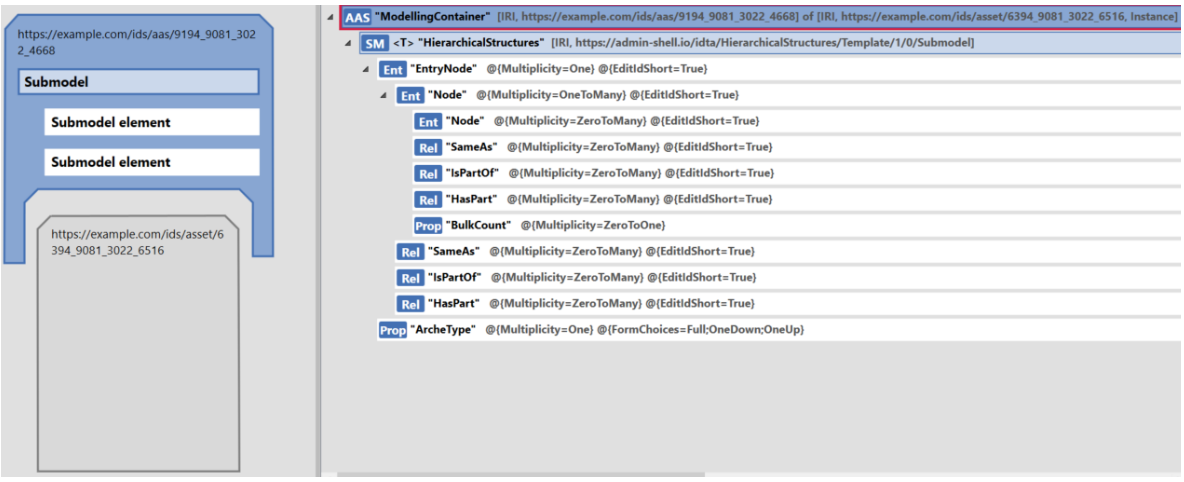


Figure 4-20. Hierarchical Structures enabling Bills of Material submodel.

The usage of the abovementioned submodel covers the following Circular TwAIn requirements:

- **Traceability**: A manufacturer may assemble a product from suppliers' subproducts or a dismantler may disassembly a product to sub products (e.g., a sample a battery pack from a number of battery cells or disassembly a battery pack to battery cells). To preserve the data that spawns from processes at (sub-)suppliers, each part should be appended with an AAS. Upon assembly, the assets are aggregated physically, consequently the AAS must be merged as well. This enables the manufacturer to identify, locate and access the AAS of all delivered products that may contain data on i.e., the source of quality deviations, carbon footprint and arbitrary other data stored in the AAS of the subsystem.
- **Production Order**: In circular economy value chains, participants continuously monitor the market for suppliers, strengthening resilience and flexibility. Automating this search requires a common interface for a production order including a formal description of all incoming components' hierarchy.

Submodel Design Considerations

In the context of circular economy, the following AAS (Asset Administration Shell) submodel design decisions where followed [Industrial Digital Twin Association, 2023]:

- **Co-managed and Self-managed Entities**: The submodel distinguishes between Co-managed Entities and Self-managed Entities using the Entity SubmodelElement. Self-managed Entities have their own AAS, while Co-managed Entities do not. This allows for the representation of products within a hierarchical structure. Differentiating between the two types of entities is important for algorithms consuming the submodel, and the "entityType" attribute can be used for this purpose.
- **Distributed and Centralized AAS**: The AAS and their Submodels can be distributed in different ways to support circular economy scenarios. The first approach is a file-based method where one or more AAS are serialized into files. The second approach is a distributed format, involving one or more AAS servers hosting multiple AAS. Assets described within the AAS can form functional units. To facilitate access to distributed information in the second approach, relations between the assets need

to be modelled within the AAS. In this submodel, only logical relations are defined to support the modelling of hierarchical structures.

- **Allowed modelling variants:** The submodel template provides options for modelling hierarchies in circular economy scenarios through different archetypes:
    - **Full**: This archetype allows for modelling a complete hierarchy, including sub-assets, within a single submodel. It is useful when representing Co-managed Entities that do not have their own AAS. Full modelling also enables the central management of version statuses. In circular economy scenarios, this can be beneficial for tracking the lifecycle of assets and their components.
    - **One Down**: The One Down archetype is suitable for subsystem or component manufacturers. Each asset in the hierarchy tree has a corresponding AAS, containing a Submodel that expresses a one-down excerpt view starting from the asset itself. This type allows for the consistent modelling of stand-alone hierarchies during the engineering phase of subsystems. It can be useful for managing and tracking individual components within circular economy systems.
    - **One Up**: The One Up relationship is used to describe the installation location of an asset. It enables the asset to provide information without relying on external asset administration shells, such as in offline scenarios. In circular economy scenarios, this can be relevant for tracking the location and status of assets during their use and disposal stages.

4.3.3 Product DT Middleware Implementation.

For the product DT Implementation, the Eclipse BaSyx[6] platform is considered to be used. BaSyx is an open-source platform (using Eclipse Public License 2.0) for next-generation automation that implements key concepts defined by Platform Industrie 4.0. BaSyx offers off-the-shelf components, SDKs, and reference application scenarios to support the development of Industrie 4.0 solutions.

BaSyx supports the following standards:

- Asset Administration Shell (AAS): BaSyx implements the AAS as a standardized Digital Twin, following the IEC 63278-1 ED1 standard.
- Functional Mockup Interface (FMI): BaSyx supports the encapsulation of simulation models as Functional Mockup Units, conforming to the FMI standard. This allows for the integration and interoperability of simulation models within the platform.
- Semantic Annotations: BaSyx supports semantic annotations conforming to standards such as ECLASS and IEC CDD IEC 61360-4. These annotations provide semantic knowledge about the meaning of properties and services, enhancing the understanding and interoperability of data.

[6] https://www.eclipse.org/basyx/

- Connectivity: BaSyx supports various connectivity options for communication between devices, systems, and the platform. Here we list some of which can be used in Circular TwAIn scenarios:
  - MQTT: It enables communication using the publish/subscribe method, allowing data exchange between edge devices and AAS Submodels or MQTT Brokers.
  - OPC-UA: BaSyx supports communication between edge devices and the BaSyx middleware, as well as direct communication with PLCs (Programmable Logic Controllers) using the OPC-UA protocol.
  - S3: Integration with S3 cloud technology brings flexibility and scalability to handle large volumes of data.

BaSyx also provides and is compatible with several applications and tools to facilitate Industrie 4.0 development and operations. In Circular TwAIn the following could be used:

- AAS Package Explorer[7]: This tool allows users to create Asset Administration Shells and AAS Submodels for assets. It supports the creation of new AAS types and submodel types.
- BaSyx AAS Viewer: It enables users to look up AAS and submodels from a registry server and view their contents. This tool helps in process tracking and monitoring.
- Eclipse Streamsheets[8]: An open-source application which allows real-time data analytics, transformation, and analysis, enhancing data-driven decision-making.
- Grafana[9]: An open-source application compatible with BaSyx, which enables the creation of dashboards and virtual control rooms, providing visualizations for monitoring and analysis.
- Node-Red[10]: An open-source application that enables the automation of reactions to events, such as detecting unusual sensor values. It can be integrated with BaSyx to enhance automation capabilities.

Detailed information about BaSyx Architecture and components can be found at the BaSyx documentation wiki page[11].

BaSyx is a conforming Industrie 4.0 production system that consists of various components, including production assets (devices, workers, products), apps, a registry, and AAS (Asset Administration Shell) and submodel providers. AAS and submodels are used to establish standardized interfaces to assets and different types of data and data sources.

In Figure 4-21 below we can find an example of the main components of BaSyx architecture deployment where the directory acts as a registry, allowing AAS and their submodels to be registered and accessed. Smart devices, which are integral to the production assets, natively support Asset Administration Shells and autonomously register themselves with the

[7] https://github.com/admin-shell-io/aasx-package-explorer
[8] https://github.com/eclipse/streamsheets
[9] https://grafana.com/
[10] https://nodered.org/
[11] https://wiki.eclipse.org/BaSyx_/_Documentation

directory. Applications, such as a dashboard application in the example, leverage AAS submodels to retrieve data from the shopfloor. This data can include information related to products and materials, such as their composition, origin, and lifecycle status. Applications can also modify property values and invoke submodel operations to control the production process, enabling the implementation of circular economy principles, such as resource optimization and waste reduction.

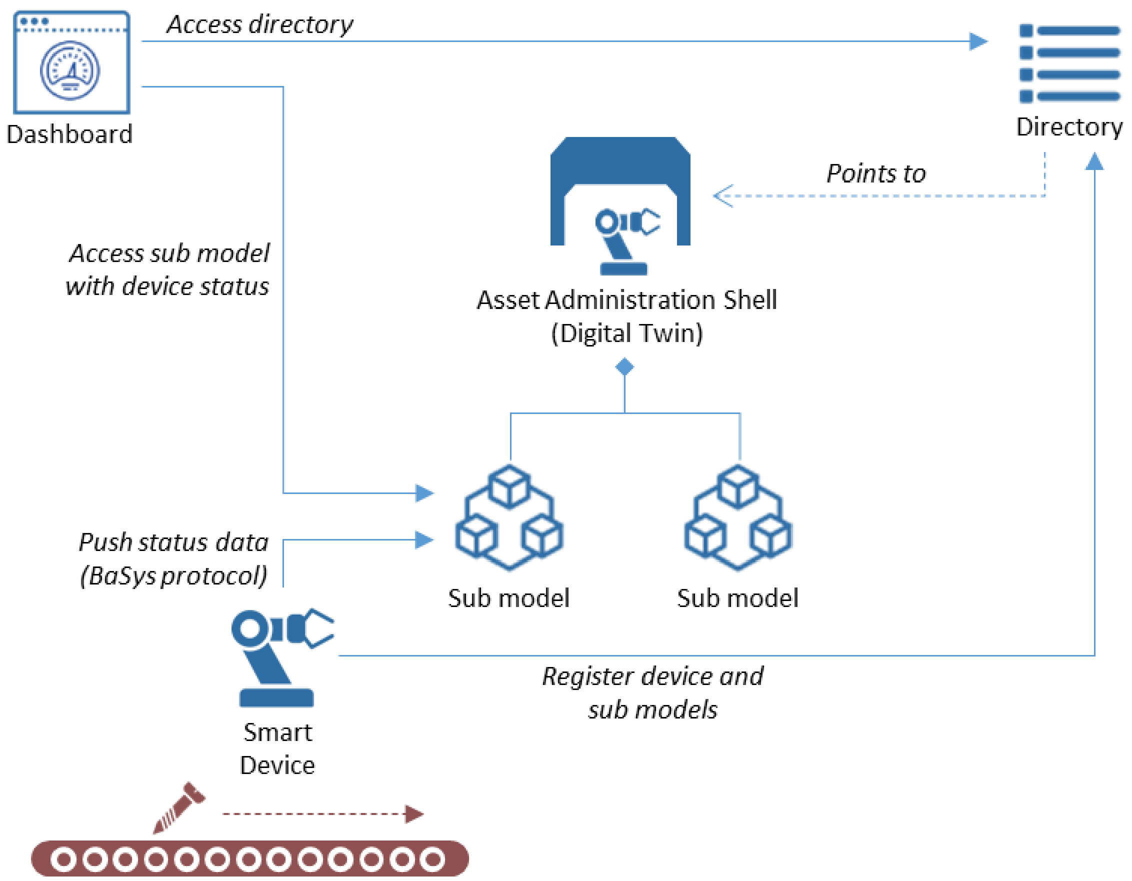


Figure 4-21. BaSyx Architecture example

The exchange and modelling of product and material data are facilitated by the unified interfaces provided by AAS and submodels. AAS enable a standardized representation of assets and their associated data, while submodels allow for the organization and structuring of data from different sources. This standardized approach supports interoperability and seamless data exchange between various components within the BaSyx architecture, enabling efficient management of products and materials throughout their lifecycle.

Additionally, BaSyx supports the integration of various data providers, including those that persist AAS and submodel data in databases. This capability allows for the integration of external systems and databases containing relevant product and material information, further enhancing the circular economy capabilities of the architecture.

Installation and usage

As mentioned above BaSyx provides several core components that can enable an AAS main functionalities. These components can be used programmatically, as an executable jar or as a docker container. Detailed installation and usage instructions can be found at the BaSyx

Wiki page[12] where all the different components are listed and the required environment configurations. More specifically the components are:

- AAS Server Component which is available here[13]
- Registry Component which is available here[14]
- DataBridge Component which is available here[15]
- AAS Web UI which is available here[16]

4.4 Human Digital Twin

4.4.1 Context Viewpoint

Input 0	Circular TwAIn Reference Architecture
Input 1	System Scope
Input 2	State-of-the-Art Analysis
Input 3	Clawdite
Input 4	Generic Objectives for HDT
Input 5	How HDT will support pilots
Output 1	List of Human DT features
Output 2	System Concept

Input 1: System Scope

The human Digital Twin scope is to model the human worker and to integrate human factors in complex manufacturing systems. The ultimate goal is to lower the barriers for humans to engage in AI-based sustainable manufacturing processes, while increasing the trust on them. Integrating the human factor in the manufacturing process is about considering humans' variability and limitations and creating an environment that enables the workers to be more efficient, safe, productive and satisfied [25]. Modern manufacturing systems must have human awareness, while keeping human decision making in the loop at different levels of automation [26].

Human workers can benefit from human Digital Twins supporting decision-making processes, minimizing environmental influences and individual skills and experience gap, and enabling human-aware technologies that can adapt to the worker's needs and facilitate human-machine interaction.

The HDT may be used to evaluate readiness of personnel who interact with the system or understand the errors and circumstances in which errors are made. Finally, the HDTs may be used to determine and assign tasks among workers or between humans and robots [27].

[12] https://wiki.eclipse.org/BaSyx_/_Documentation_/_Components
[13] https://wiki.eclipse.org/BaSyx_/_Documentation_/_Components_/_AAS_Server
[14] https://wiki.eclipse.org/BaSyx_/_Documentation_/_Components_/_Registry
[15] https://wiki.eclipse.org/BaSyx_/_Documentation_/_Components_/_DataBridge
[16] https://wiki.eclipse.org/BaSyx_/_Documentation_/_Components_/_AAS_Web_UI

The adoption of circular economy strategies is expected to have a positive effect on job creation provided that workers acquire the skills required by the green transition [28].

Recent studies suggest that most 'green jobs' require an upskilling of the labour force and that the mobility and transferability of skills will play an important role as value chains and sectors undergo changes [29]. Human Digital Twins modelling workers' skills and experience can also support worker's up-skilling and re-skilling.

Input 2: State-of-the-Art Analysis

To enhance human-machine interaction in industrial settings, new categories of industrial machinery have emerged, such as collaborative robots and autonomous mobile robots (AMRs). However, these advancements necessitate the development of systems capable of managing the inherent stochastic nature and uncertainty associated with human operators. Unfortunately, the focus of Industry 4.0 (I4.0) standards has primarily been on creating digital representations of machines and assets, often overlooking the significance of human involvement in production systems. The Asset Administration Shell (AAS), a fundamental component outlined by the I4.0 consortium for establishing interoperable digital representations of assets, does not encompass humans as integral entities within factory environments. Consequently, designing a comprehensive model that captures the stochastic nature of human operators remains a challenging task. Several solutions have been proposed to address this limitation by introducing the concept of the Human Digital Twin (HDT) to create digital representations, either providing a high-level perspective of operators [30] or creating more complex digital representations of human operators [31]–[36]. By incorporating uncertainty, HDT aims to emulate human behaviour, encompassing a comprehensive representation of **humans' skills** and providing estimates of their current status. By incorporating a more nuanced and detailed representation of humans, an HDT can capture the intricacies of human behaviour within industrial settings. This includes factors such as their **expertise**, **experience**, and **capabilities**, enabling a more accurate reflection of their impact on production processes. Additionally, an HDT can dynamically assess and update the current status of workers, considering factors like workload, fatigue, and **skill utilization**. This capability empowers decision-makers to anticipate and mitigate risks proactively while identifying opportunities for improvement.

Circular TwAIn foresees a strong alignment with the Reference Architecture Model for Industrie 4.0 (RAMI4.0), and thus promotes the adoption of the Asset Administration Shell (AAS) for defining DTs. Although AAS serves as a valuable tool for representing and managing physical assets within industrial systems, it does not directly tackle the representation and management of humans, primarily focuses on digital representations of machines and assets. However, how to extend AAS with a digital representation of humans is still an open issue, opening to interesting research questions (e.g., "How to represent a human being in a standardised structure defined for physical and unanimous assets?"). Some efforts have been made in literature in proposing a Human-Asset Administration Shell (H-AAS) [37], [38], but a proper formalization of the human in the AAS is still lacking, leaving some open points (e.g., how to structure the sub-models, which kind of data should be stored in addition to the live data coming from other assets).

EUROPEAN RESEARCH PROJECTS

Table 4-8 - European Research Projects related to HDTs

Project Name	Project Details	Involved Partners
AI-REGIO	https://www.airegio-project.eu	POLIMI, NISSATECH, ENG, SUITE5, TECNALIA, ENGINEERING
KITT4SME	https://kitt4sme.eu	SUPSI
HUMAN	http://humanmanufacturing.eu/	SUPSI
STAR	https://star-ai.eu/	GFT, SUPSI

HUMAN DIGITAL MODELS

The domain of machinery encompasses a wide range of standards and definitions specifically tailored to describe assets. One notable industrial standard is eCl@ss, which adheres to ISO/IEC guidelines and provides tens of thousands of product classes and unique properties to standardize procurement, storage, production, and distribution activities across companies, sectors, countries, and languages.

Again, when it comes to human-related industrial standards, there is a noticeable lack of comprehensive frameworks in the literature and international standards organizations. Although taxonomies for human skills do exist, such as ESCO (Classification of European Skills, Competences, Qualifications, and Occupations) and O*Net (Occupational Information Network), they do not fully address the broader scope of human factors in industrial settings.

While few other standards and taxonomies have been proposed in the literature, they cover specific aspects [39]–[41]. Additionally, the ISA-95 personnel model offers an abstract framework for defining employees and their roles [42].

Overall, the existing literature and standards organizations still lack comprehensive and widely adopted industrial standards that specifically address the representation and management of human factors within the machinery domain. Efforts to develop robust and encompassing frameworks for human-related standards can greatly enhance the understanding and optimization of human-machine interactions in industrial contexts.

Recognizing the existing limitation of industrial standards regarding human representation, the HDT proposed in Circular TwAIn takes a significant step forward by building upon a dedicated generic meta-model [43]. This meta-model is specifically designed to facilitate the composition of HDTs, providing the essential classes required to create a comprehensive representation. The development of a model specifically tailored for HDTs in Circular TwAIn addresses the need for a comprehensive representation of humans in industrial systems.

Input 3: Clawdite

The Clawdite platform addresses the recurring need for a solution capable of supporting the creation of DTs in various manufacturing applications [44]. Previous scientific work and European funded projects have demonstrated that instantiating the digital representation of factory entities, such as workers, cobots, and workstations, requires significant effort in terms of modelling, infrastructure development, configuration, and deployment. However, the reusability of these solutions and DTs is often limited.

To overcome these challenges, the Clawdite platform employs a modular architecture, featuring the following components:

- Agents and Gateways as standardized interfaces for accessing available data, ensuring data harmonization and facilitating the implementation of data gateways by using shared data formats and lightweight formats to minimize overhead.
- Multiple IIoT Middlewares, enabling data streams to be shared among components, while the Orchestrator defines message structures and schemas for efficient communication.
- Orchestrator, a central component that organizes and manages the platform and its DT instances, providing a REST API for retrieving data and allowing administrators to define entities and connect modules, while GUIs enable visualization of data and metrics.
- Historical Data Manager: responsible for persisting historical data, specifically time series data flowing into the IIoT Middleware. Storing historical data allows for reporting and analytics activities.

By leveraging these components and functionalities, the Clawdite platform offers a robust and flexible architecture for creating and managing DTs, addressing challenges related to modelling efforts, infrastructure development, configuration, deployment, and reusability of solutions.

Input 4: Generic Objectives for HDT

As briefly discussed in Input 2, HDTs have been exploited in literature to create different digital representations, either providing a high-level perspective of operators, or creating more complex representations of human operators to emulate human behaviour, encompassing a comprehensive representation of humans' skills and providing estimates of their status.

The HDT developed in Circular TwAIn will focus on modelling workers' skills and knowledge, by capturing factors such as **expertise**, **experience**, and **capabilities**, enabling a more accurate reflection of their impact on production processes.

Table 4-9 - HDT Generic Objectives

ID	Objective	Rationale/Notes
Obj1	Increase workers' AI acceptance.	If AI-based systems can adapt to workers' needs and ability, this can increase AI acceptance.
Obj2	Increase workers' trust on AI.	If AI-based systems can explain their decisions and adapt such explanation to the workers' level of understanding, this can increase trust.
Obj3	Support human in decision making processes.	
Obj4	Improve workers engagement in (de-/re-) manufacturing tasks.	Tailoring manufacturing tasks on human capabilities may increase their engagement (e.g., by avoiding tasks that may be perceived as "hard" because of lack of experience).

Obj5	Enable human centric sustainable manufacturing.	Humans' capabilities must be taken into account when defining processes (e.g., the same collaboration strategy may not apply with different workers with different skills).
Obj6	Support upskilling and reskilling.	If a worker is supposed to complete a task given its level of skills, but many failures happen, then the worker possibly needs upskilling/reskilling.

Input5: How HDT will support Pilots

Workers' knowledge/expertise/skills modelled in the twin can support the Pilots in different ways. We have identified some possible application for each Pilot, however feasibility evaluation is still ongoing. The identified applications are descripted below:

- **PETRO**: decisions and feedbacks from operators can be weighted based on their knowledge (e.g., workers can be more or less experienced to detect tricky anomalies, or some specific types of anomalies). The XAI tools and Decision-Making tools will be supported by the HDT, so that to "decide" if they can trust the current action of the operator.
- **WEEE**: the Process DT adapts its visualization/explanations based on the operator knowledge, which can be fetched from the HDT. Also, feedback provided by operators can be weighted based on their expertise/skills.
- **BATTERY**: in case the worker is less experienced additional safety-related measures can be put in place, risky activities (e.g., battery disassembly) are not assigned, or additional guidelines and reminders can be displayed.

Table 4-10 - Battery pilot use cases mapping with HDT Generic Objectives

BATTERY		
Digital Assembly and Machines		
UC. A	Computer-vision driven collaborative robotics for the disassembly of LIB packs	Obj1, Obj2, Obj4, Obj5, Obj6
UC. B	Machine learning aided automated disassembly of LIB modules	Obj1, Obj2, Obj4, Obj5, Obj6
E2E Planning		
UC. E	Market-oriented holistic decision-support-system for WEEE de- and re-manufacturing	Obj1, Obj2, Obj3

Table 4-11 - WEEE pilot use cases mapping with HDT Generic Objectives

WEEE		
Digital Assembly and Machines		
UC. C	Real time planning of the disassembling operations	Obj1, Obj2, Obj4, Obj5

UC. D	Collaborative Robotics for the support of manual operations	Obj4, Obj5, Obj6
E2E Planning		
UC. E	Market-oriented holistic decision-support-system for WEEE de- and re-manufacturing	Obj1, Obj2, Obj3

Table 4-12 - Petrochemical pilot use cases mapping with HDT Generic Objectives

PETROLCHEMICAL		
Digital Performance Management		
UC. B	Developing a hybrid circular twin of the process	Obj1, Obj2, Obj3, Obj6
UC. E	Generation of a tool for process optimization	Obj1, Obj2, Obj3, Obj6

Output 1: List of Human DT features

Table 4-13 - List of Human DT features

ID	Feature	Description
HDT-f1	Real-time data sharing	The worker's inputs are transmitted to the HDT in real-time.
HDT-f2	Interoperability with external systems	The HDT should be easily integrated with other software systems (e.g., data spaces, dashboards, …).
HDT-f3	Interoperability with other DTs (product and process)	The HDT should be able to interact with the process DT.
HDT-f4	Skills modelling	The HDT should be able to model most relevant skills.
HDT-f5	Worker's task modelling	The HDT should know which are the worker's task and which ability are required for the specific task.
HDT-f6	Supporting AI (/XAI) modules	The HDT should be able to support AI (/XAI) modules both embedded and as a service.

Output 2: System Concept

The Human DT will be deployed in organizations where the information about workers' skills and capabilities is very relevant to the production process (e.g., in collaborative robotics environments, where a cobot may adapt to the limited skills of an operator). The HDT can also be supported by AI techniques, estimating additional worker's properties from historical results.

For these reasons, the foreseen HDT is a crucial support for any decision system, as well as the process DT developed within the Project, which can take into consideration the additional information provided by HDT in making predictions and simulation about the ongoing process.

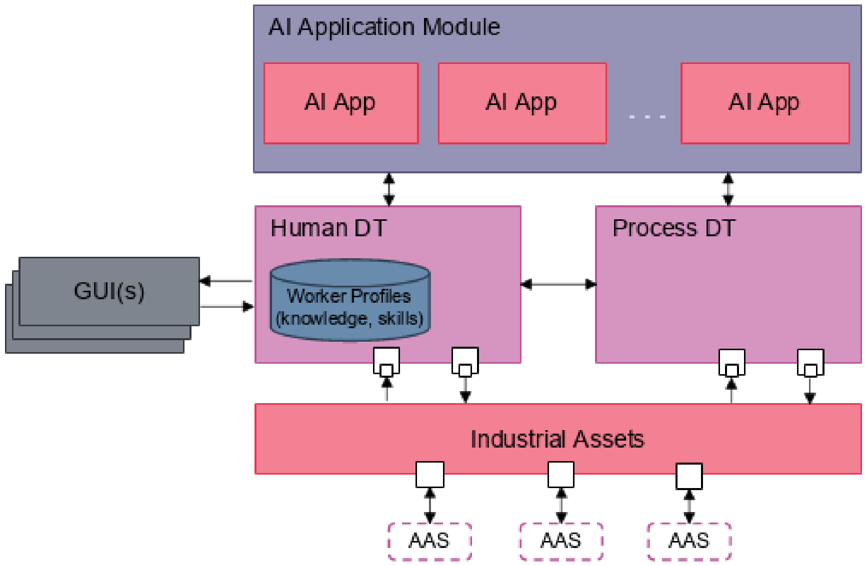


Figure 4-22. HDT System Concept

4.4.2 Functional Viewpoint

Logical Level Design

The Figure 4-22 shows the preliminary architecture of the Human DT. Within the Project, the Human DT shall represent workers' skills and knowledge, by capturing factors such as **expertise**, **experience**, and **capabilities**, without supporting real-time interactions. The architecture has been designed for pursuing Project''s objectives, regardless the functionalities already available in Clawdite. However, thanks to the high flexibility of Clawdite, most of the subcomponent of the Human DT can be mapped to existing modules in Clawdite. The mapping is represented in Figure 4-23 and Figure 4-24 by means of square boxes (If two components share the same color, then they provide almost the same functionalities, with slight differences). Missing components requiring Clawdite extensions are highlighted with shadowed boxes.

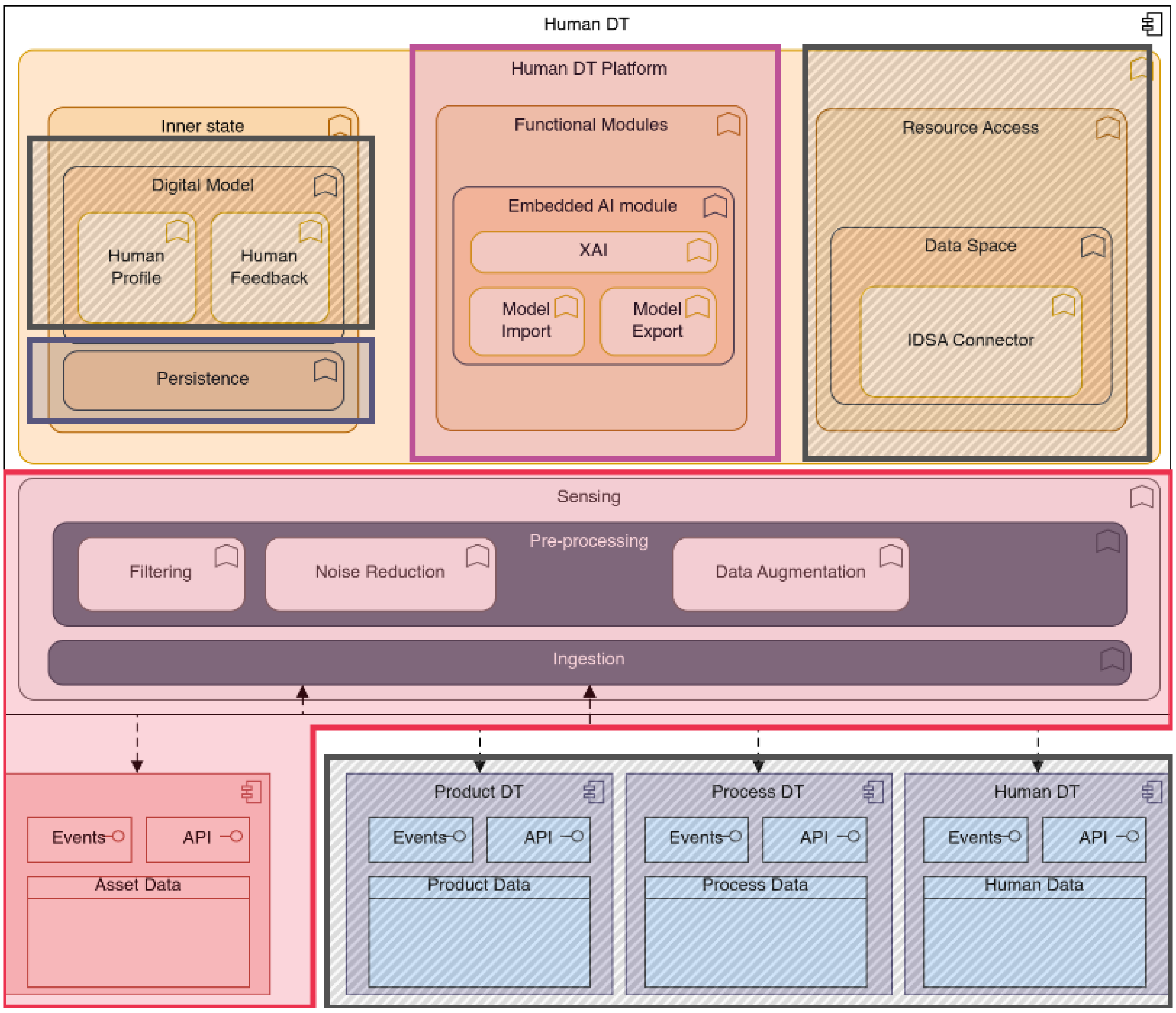


Figure 4-23. HDT Logical Architecture

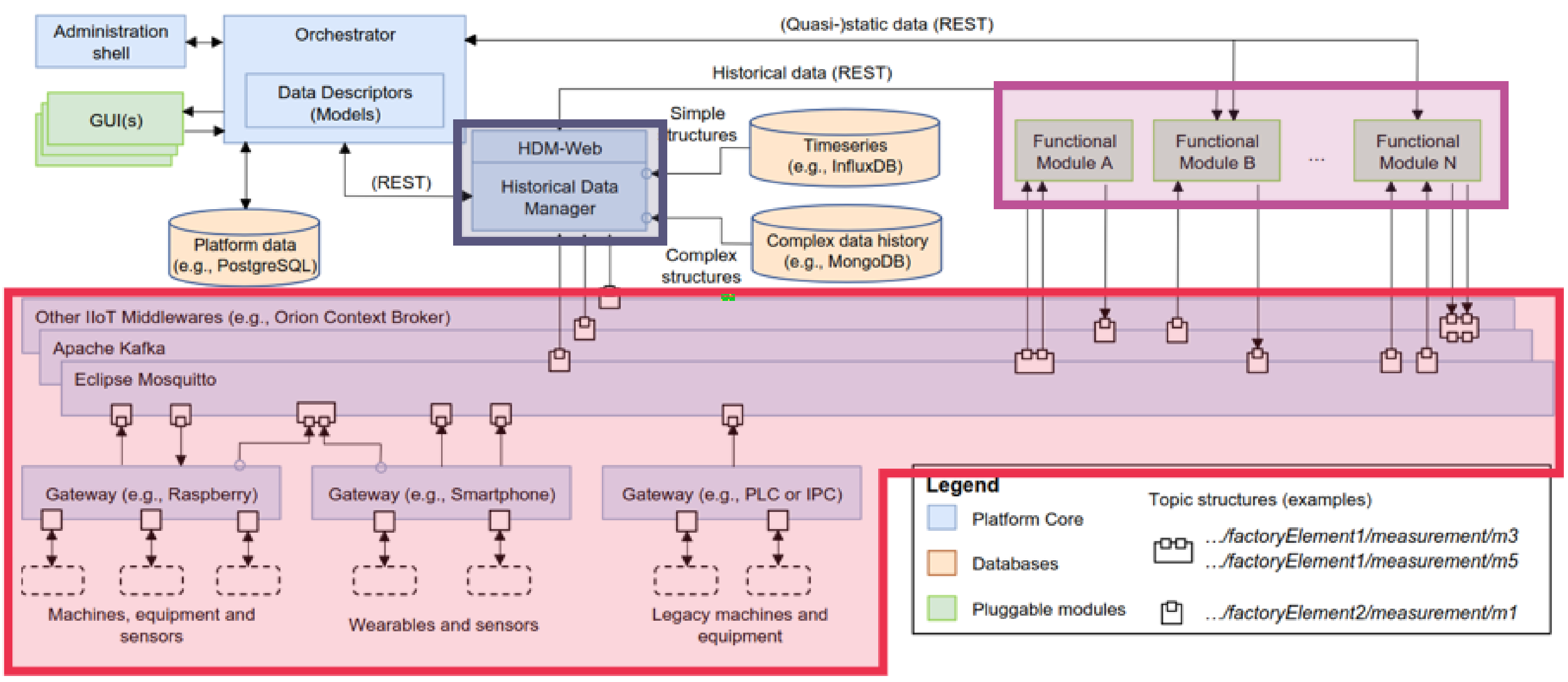


Figure 4-24. Clawdite Architecture

Subsystem and components

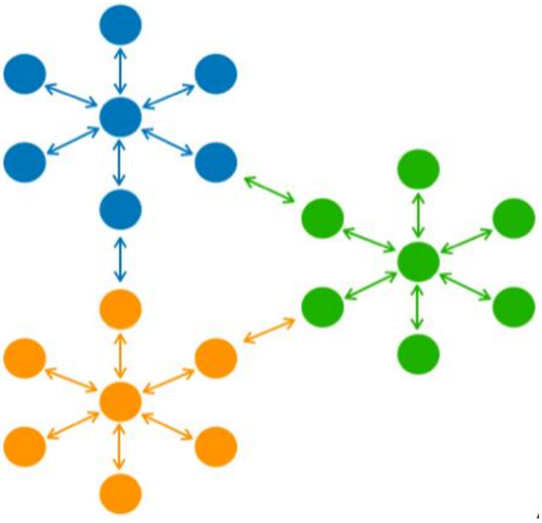
In this section, we describe the components that are part of the Human DT architecture.

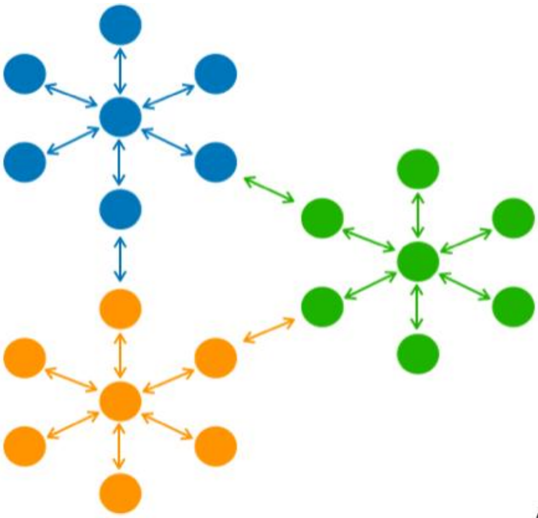
Subsystem	
Name	Human DT
Interfaces	- REST API (e.g., for DT to DT communication) - MQTT Event-based communication (e.g., for reading data from assets)
External Entities	- Product DT - Process DT
Processes/Responsibilities	Designed to collect and maintain data related to workers' **expertise**, **experience**, and **capabilities.**
Notes	

Component	
Name	Inner State
Component/Responsibilities	Internal representation of the human (e.g., roles in the company, relevant working skills). Mainly composed by human profiles and feedback (to keep track of wrong results or suggestions).
Notes	In case of transient data (e.g., sent to an MQTT server), the Human DT should provide a mechanism to create persistence out from transient data. For this reason, the Inner State component comes with a specific "Persistence" subcomponent.

Component	
Name	Functional Modules
Component/Responsibilities	Functional Modules predict/ understand the internal state also based on collected feedbacks. These modules are supposed to be mainly AI-driven application, represented in Figure 4-22 is "Embedded AI". The modules can extract new evidence from the Human DT knowledge, or provide new knowledge to the Human DT from external sources. AI models available in the Human DT should be easily exportable, as well as new models should be easy to import to update the AI core of the DT.
Notes	Clawdite already comes with the concept of functional modules providing new "States" for the DT.

Component	
Name	Resource Access

Component/Responsibilities	This is a block required for communicating with digital Data Spaces. This component will include the relevant IDSA connectors for accessing the needed information. 
Notes	

Component	
Name	Sensing
Component/Responsibilities	Ingest data into the Human DT, with a light preprocessing when needed (e.g., filtering, noise reduction, data augmentation). 
Notes	While Clawdite is already compatible with different data brokers (i.e., MQTT, FIWARE Orion Context Broker), new connectors are needed to extend this functionality, e.g., to interact with other twins.

4.4.3 Process Viewpoint

In the context of Circular TwAIn, the Human DT is mainly intended to work in a pull-based fashion. In detail, the Human DT should expose an interface (e.g., REST API) to make external components (e.g., Process DT) to access its knowledge.

However, the push-based communication mechanism will be supported as well, so that to enable external components to be notified whenever some changes happen in the Human DT.

Having a pull and push-based communication mechanism in place, the Human DT can support the event-based communication. However, at the writing time, events to be exchanged with the Human DT have to be defined yet. However, thanks to the high-flexibility of the Clawdite model (which will be exploited as the basis for the Human DT development), new events can be easily modeled and made available to external components. Indeed, for each event message shared within the Human DT, Clawdite has its related data schema description.

4.4.4 Information Viewpoint

As discussed in section 4.4.1 - Input 2, AAS sub-model templates are not currently available for humans, thus new models are needed to represent humans in DTs. By leveraging a generic meta-model [43] in Circular Twin we start from the Clawdite data model to represent the information needed by the Human DT. In the following, we provide details about the Clawdite data model (depicted in Figure 4-25)[17].

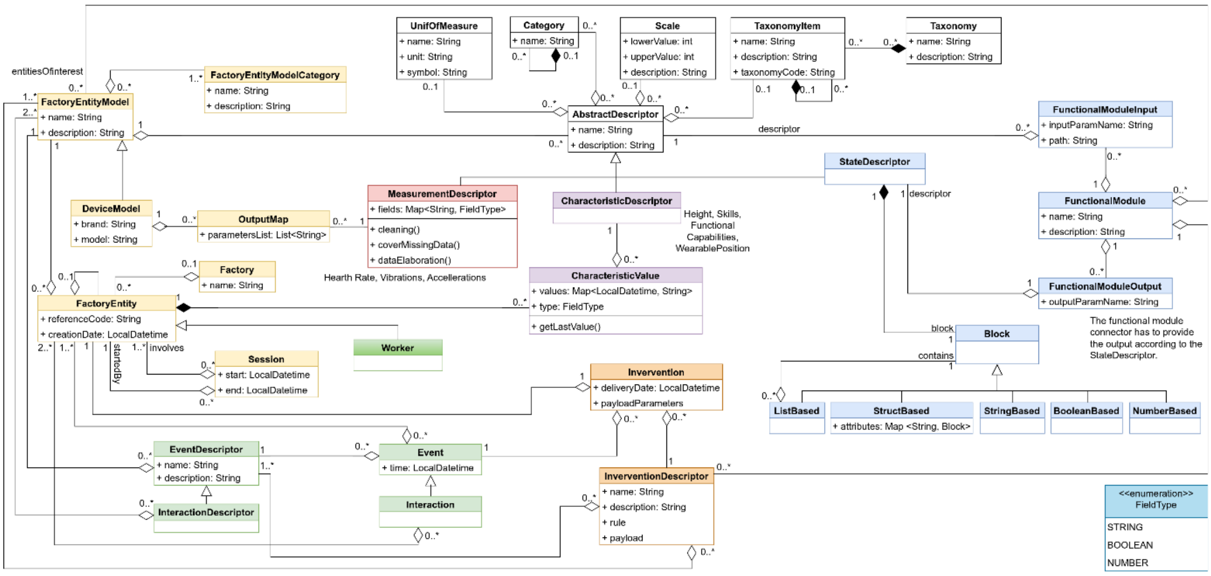


Figure 4-25. Clawdite Reference Model

Component	
Name	Abstract Descriptor (white, red, purple, light blue)
Component/Responsibilities	High-level description of any type of data managed by the HDT: characteristics, measurements and states.

[17] *Without adding extra complexity to this document, we describe macro-categories of entities in the data models, which are identified by different colours in Figure 4-25.*

	Characteristics mainly refer to static attributes characterising entities (e.g., workers skills, job position), which change slowly over time (*slow data*). States are evolving attributes of entities (e.g., next task to be performed by a worker). Measurements are attributes gathered from sensors (e.g., worker's heart rate from a wearable device), often gathered at high frequencies (*fast* data).
Notes	

Component	
Name	Production System Models (yellow)
Component/Responsibilities	Definition of all the entities acting in the factory, monitored by the HDT. Entities can be grouped by means of "models" (e.g., several instances of wearable devices share the same device model).
Notes	

Component	
Name	Worker (green)
Component/Responsibilities	It represents workers in the production system. This entity inherits from FactoryEntity, but provides fine-grained management and enabling additional data preservation rules for worker-related measurements (e.g., workers can be anonymized within the HDT, unlike other factory entities).
Notes	

Component	
Name	Functional Modules (light blue)
Component/Responsibilities	This entity models any model attached to the HDT, also describing its input/output in terms of Descriptors. Functional modules are expected to update the State of some entities represented in the HDT.
Notes	In the context of Circular TwAIn, functional modules are represented by AI modules.

Component	
Name	Events and Interactions (green)
Component/Responsibilities	The data model also foresees the description of events and interactions happening between entities. For example, an event between two workers may represent.
Notes	The main difference between events and interaction is that interactions must involve at least 2 entities (e.g., 2 workers, 1 worker and 2 robots, etc.)

Component	
Name	Interventions (orange)
Component/Responsibilities	This section of the data model enables the definition of interventions that can be triggered to orchestrate the production system. In the context of Circular TwAIn, an intervention may be to send a notification to a non-expert operator, reminding some safety rules before preforming a risky operation.
Notes	

4.5 Rapid Prototyping

The current document provides a detailed blueprint that outlines the functionality and the behaviour of the software system the Project aims to build. Therefore, it develops the necessary views and viewpoints that are necessary to ensure a complete understanding of the system's features and behaviour. The document emphasizes the "what" rather than the "how". For this reason, views and viewpoints such as Development, Deployment and Operational are beyond the scope of this version of the document. However, since one of the main assumptions is the usage of agile development methodologies – FDD specifically – then the combination with Rapid Prototyping allows for the early validation and visualization of the features, facilitating quick feedback and design refinement. By using the rapid prototyping techniques within the FDD framework stakeholders and development teams can collaborate effectively, validating the feature design and usability early in the process. To implement the rapid prototyping strategy there is no need to have a complete infrastructure, i.e., to have the Development, Deployment and Operational views in place (these views will be developed once the software components will be integrated in the pilot's systems). On the contrary, we are relying on simulation for building scenarios – very similar to the ones suggested by the Project's industrial partners – that can be used to showcase the capabilities of the DTs and the related features. The Figure 4-26 shows an example of the approach where a quality inspection and palletizing scenario has been built to show system's features. This scenario is aligned with WEEE and BATT pilots where visual inspection for quality and diagnosis are two of the several defined use cases.

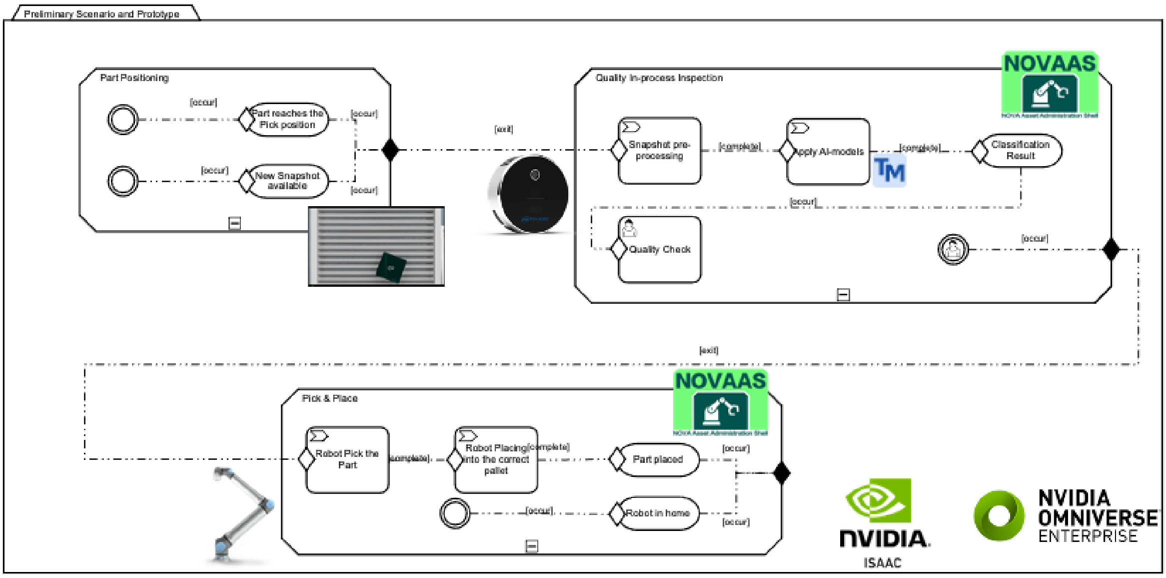


Figure 4-26. Prototype representation using Case Management (CMMN) Diagram

The prototype shown in Figure 4-26, is the synthesis of the analysis performed by the Work Package 5 (WP5) partners for the WEEE and BATT pilots. These two pilots share a lot of commonalities in processes and operational activities that allowed for the identification of one common scenario to be used as generic prototype for showcasing DTs's features. For each one of the one of the processes and tasks we tried to instantiate each one of the DT and identify the information flow. Figure 4-27 and Figure 4-28, show the result of the analysis for the WEEE and BATTERY pilots. As shown in the figures, the two pilots have several commonalities that allowed the design of a generic prototype that focuses on visual-inspection activities during the *Classification* stage (see Figure 4-26). By developing the prototype, the overall WP5 benefited since the beginning of the development activities from the promptly industrial partner's feedback about the DTs's features as well as their alignment with the overall objectives of the pilots.

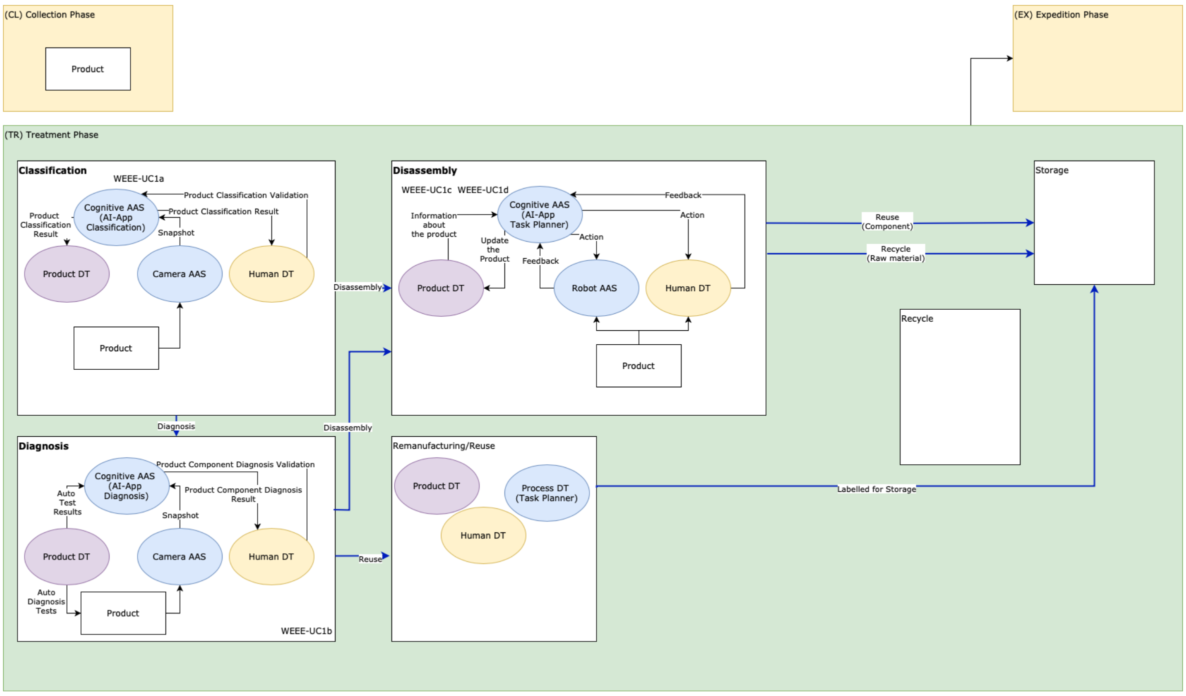


Figure 4-27. Main processes and operational tasks in WEEE and Instantiation of the Product, Process and Human DT

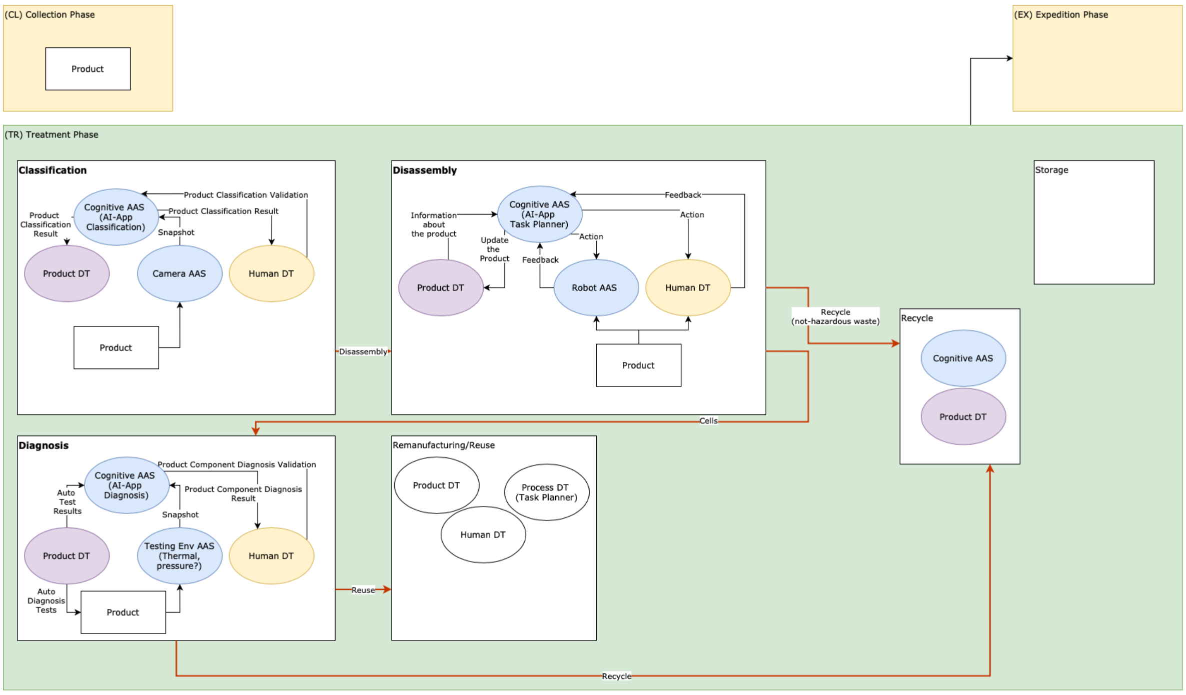


Figure 4-28. Main processes and operational tasks in BATT and Instantiation of the Product, Process and Human DT

The scenario has been implemented using the technological stack in Table 4-14.

Table 4-14. Prototype Technological Stack

Robotic Operating System	https://www.ros.org
MQTT Broker	https://www.emqx.io
NVIDIA Isaac	https://www.nvidia.com/en-us/deep-learning-ai/industries/robotics/
NOVA Asset Administration Shell	https://gitlab.com/novaas/catalog/nova-school-of-science-and-technology/novaas
AASX Package Explorer	https://github.com/admin-shell-io/aasx-package-explorer
Teachable Machines	https://teachablemachine.withgoogle.com

The Figure 4-29 shows the simulated quality inspection and palletizing station. The prototype combines two main features: inspecting the quality of the products (by using a camera) and efficiently arranging them on pallets for storage or shipping. The system is designed to ensure that products meet the required standards before they are packaged.

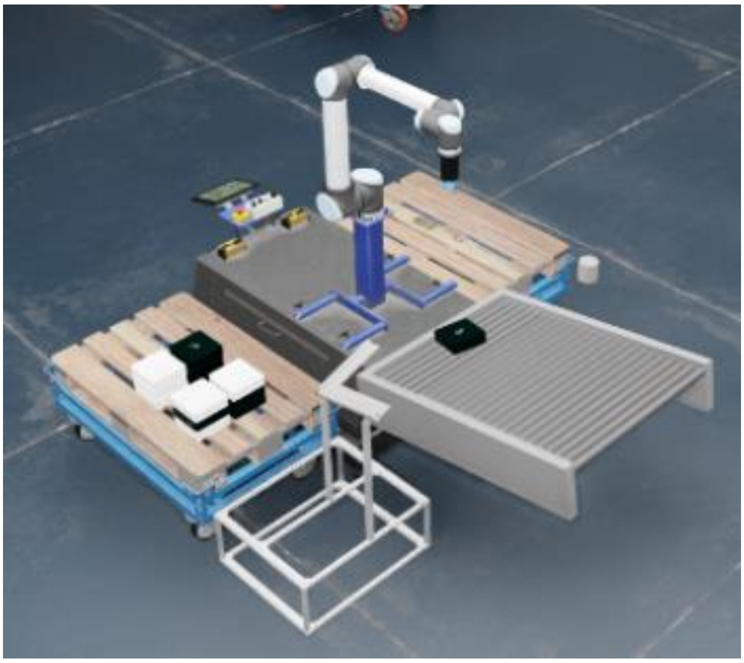


Figure 4-29. Prototype overview in NVIDIA ISAAC

One of the key features and processes involved in the prototype is the *Visual Inspection*. *Visual Inspection* feature relies one AI-models to automatically examine each product, looking for defects, irregularities, or any other issue. The Figure 4-30 shows an example of two products with different quality level (represented by a different colour of the product case).

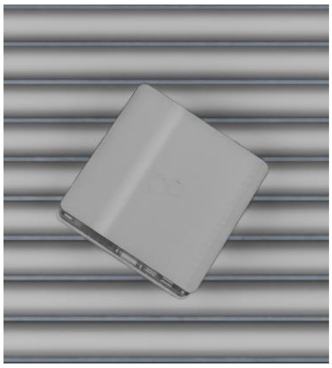



Figure 4-30. Products with different quality level

The AI models have been trained using *TeachableMachines* tool (see Figure 4-31). Three distinct quality levels have been created. The execution of the model is performed directly by the Process DT to show how AI-enhanced DT could operate.

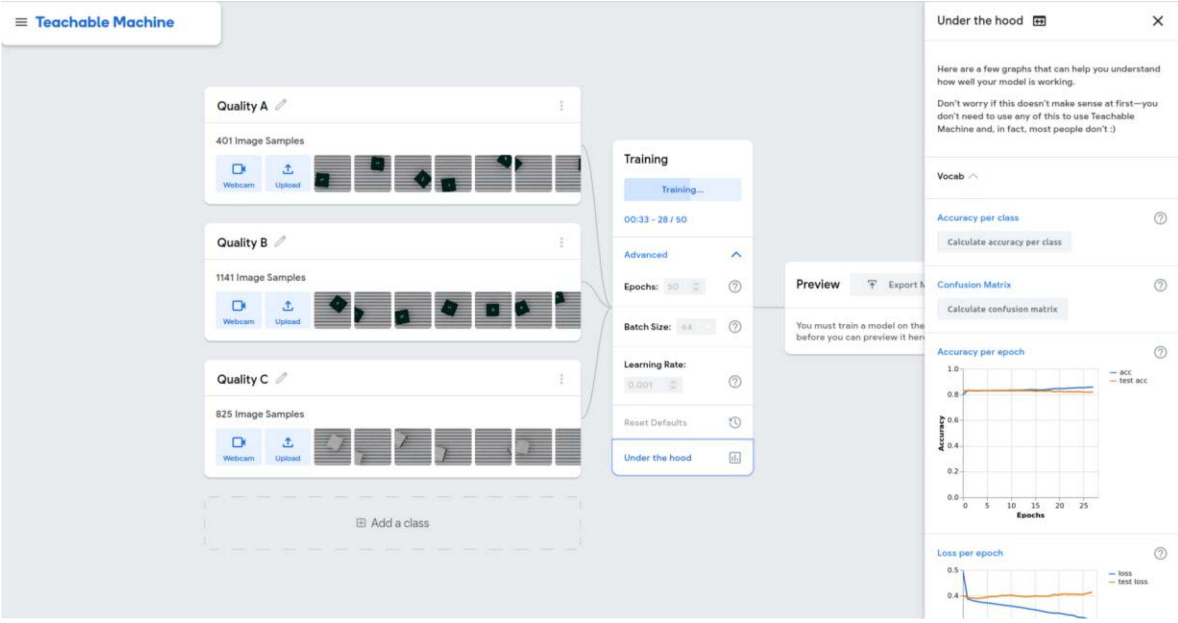


Figure 4-31: Training the AI models for quality inspection using TeachableMachines

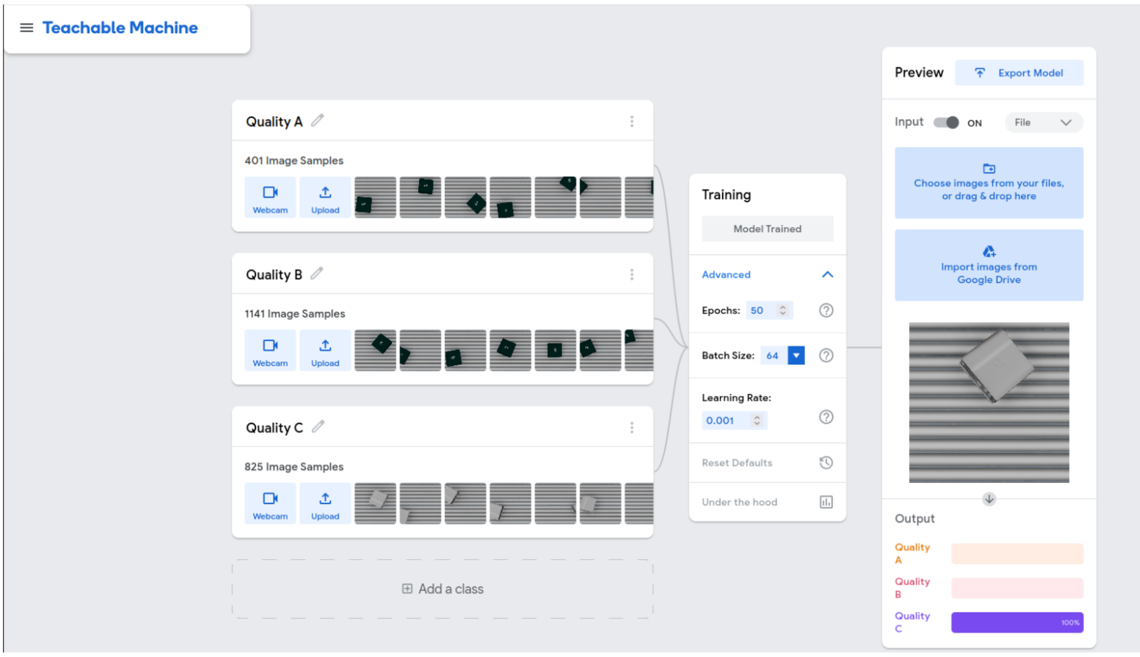


Figure 4-32. Applying the AI model for quality inspection

Since Process DT will be implemented according to the AAS standard and specifications then we decided to use NOVAAS for highlighting the following key features of an AAS:

- Asset Description: the AAS meta model allows for describing almost all the information about a physical asset, such as physical characteristics, technical specifications, documentation, operational data and events. An example of the instantiation of the AAS metamodel in the context of the prototype is shown in Figure 4-33.
- Extensibility and Adaptability: how the AAS can be easily extended and adapted to various use cases and industries.

- Interoperability and modularity: The AAS is a promising standard to achieve interoperability of production assets. The implementation of the AAS for digitalizing assets enables production equipment and any application for monitoring and control to intercommunicate seamlessly thanks to its potential in providing standardized and modular information about assets and related events.
- AI and Analytics: the AAS can pre-process and process real-time data by executing pre-trained AI models. AI models can be – in turn – embedded within the AAS (as we shown in the prototype) or can be used as-a-service.

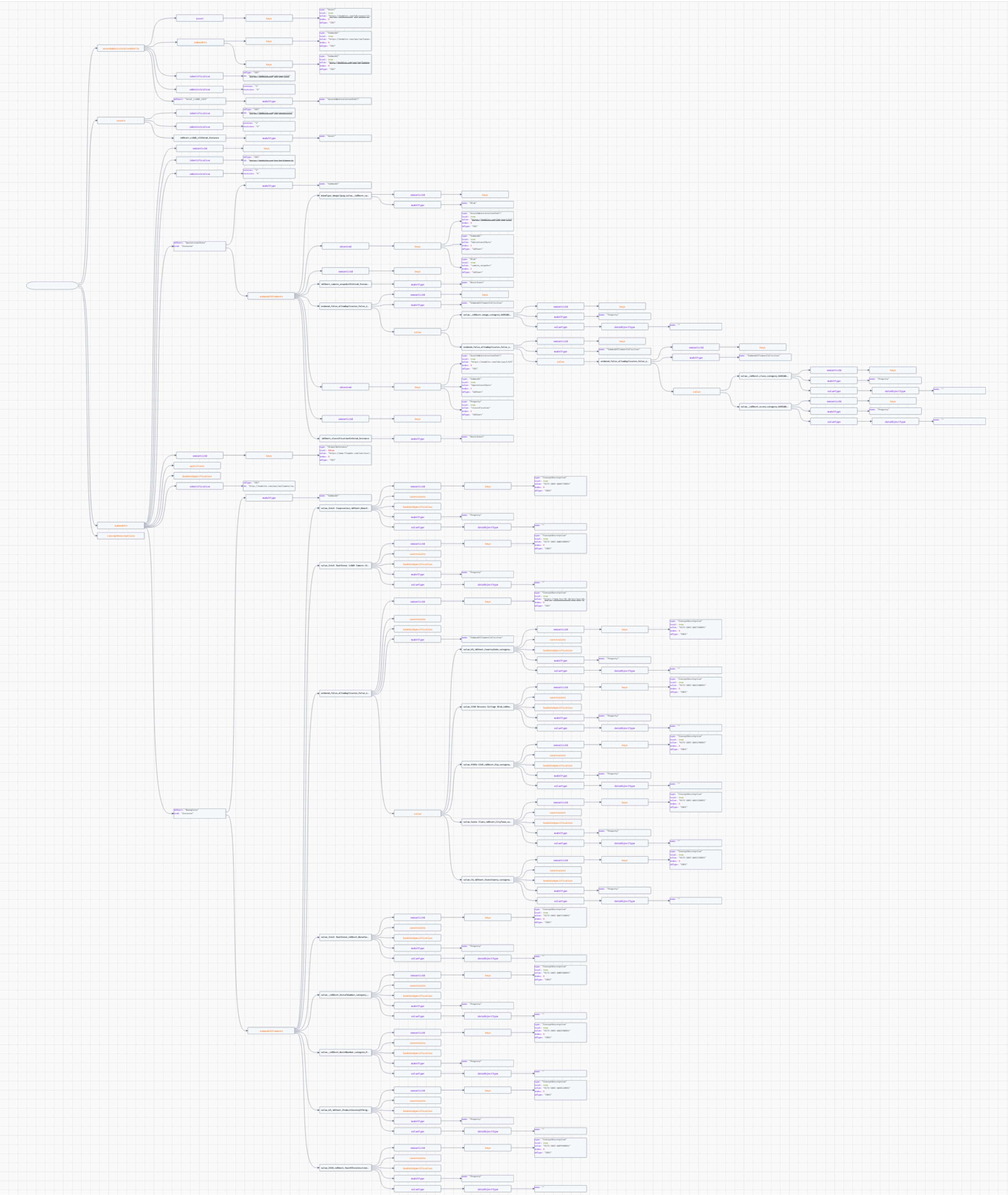


Figure 4-33. Example of the AAS metamodel developed for the simulated camera

5 Conclusion and Future Outlook

In conclusion, this document has presented the specification of Digital Twins (DTs) in the context of circular manufacturing, emphasizing three critical aspects: product, process, and human DTs. The adoption of DTs in circular manufacturing holds significant potential for driving sustainability, resource efficiency, and innovation. By leveraging real-time data and advanced analytics, DTs enable companies to optimize product design, enhance manufacturing processes, and empower the workforce. The document is aimed to develop and deliver a standardized framework for building interoperable and AI-enabled DTs that can be seamless integrated and enable the communication and data sharing between various DTs, systems, and stakeholders. This will facilitate the exchange of data, knowledge, and best practices across the circular manufacturing ecosystem. The complexity of such a framework requires a well-defined and strong strategy that can be use as the foundation for the development of the DTs. Therefore, the first version of the document is dedicated to the development of the theoretical framework – by selecting the most suitable strategy – for defining a system populated by DTs. To handle the complexity, we decided to follow the *just enough* approach to concentrate the specification effort only on the areas/facets that are necessary to build complex systems [45]. The selected areas/facets are Context, Functional, Information, Concurrency/Process, Development, Deployment and Operational. At this stage the following view has been documented, namely: Context, Functional, Information, and Concurrency/Process. The second version of the document will be focused on the development, deployment, and operational aspects of the system.

Even if several aspects of the DTs are already defined in this version of the document, they can suffer an update as the research and development activities will progress. This includes exploring advanced analytics techniques such as artificial intelligence and machine learning algorithms to enable more accurate predictions, proactive maintenance, visual inspection, and optimization of circular manufacturing processes. Additionally, investigating the potential of emerging technologies such as augmented reality (AR), collaborative robotics, eXplainable AI (XAI), etc. can further enhance the effectiveness and efficiency of DT-enabled circular manufacturing. In summary, the future work entails refining and expanding the DT capabilities, working on interoperability, exploring advanced analytics, and emerging technologies, addressing data security and privacy concerns, and fostering collaboration across stakeholders. Addressing these concerns will result in the development, deployment and operationalization of a platform based on DTs for circular manufacturing that will be fully documented in the second and last version of this document.

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