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MASIMO – DIGITAL PRODUCT PASSPORT AND AUTONOMOUS EVENT MANAGEMENT OF INDUSTRY 4.0 COMPONENTS WITH PROACTIVE AAS IN DATA-DRIVEN AVIATION MAINTENANCE AND PRODUCTION

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Abstract

This paper presents a preliminary design and implementation of a Digital Product Passport (DPP) within a proactive Asset Administration Shell (AAS) framework. Leveraging the AAS's standardized structure, the DPP enables consistent data communication across domains and technologies, facilitating seamless information exchange within the IoT ecosystem, such as between aircraft and MRO service providers or between components and manufacturing systems. Drawing from established DPP approaches in other sectors, this paper proposes a general structure for the DPP, designed to be adaptable to specific use cases in aviation. The DPP's content is flexible and includes a mandatory nameplate, as well as optional elements like a bill of materials, technical specifications, ecological data to meet future EU regulations, and digitized documents such as certifications or CAD files.

1. INTRODUCTION

In the aerospace industry, especially within Maintenance, Repair, and Overhaul (MRO) operations, the efficient management and traceability of materials and components are essential for safety, compliance, and sustainability. Increasing regulatory and market pressures emphasize the need for transparent, standardized methods to track product information throughout an asset's lifecycle. To address these needs, the EU's *Ecodesign for Sustainable Products Regulation* (ESPR) [48] introduces principles of a Digital Product Passport (DPP) to improve the circular economy and sustainability and calls for its implementation by 2027, starting with batteries. The DPP is a digital concept designed to store and provide comprehensive information about a product throughout its entire lifecycle on a common ground. It "*will form a key regulatory element of the ESPR by enhancing the traceability of products and their components*" [49]. There are a variety of names for these passports, such as "material passport", "building renovation passport" or "circularity passport", but this paper will use the term "product passport" as defined by the European Commission in order to use a domain-neutral generic term.

Due to the EU requirements, its DPP concept is currently closely linked to sustainability goals, especially in the context of the circular economy, where resources are managed in a more efficient, transparent, and sustainable way. Additionally, the DPP will play a central role in supply chains, such as those in the aerospace industry, by enabling seamless tracking of materials and components, improving transparency, traceability, and accountability at each stage of the product's path from production to disposal. Related to this, the DPP ensures that all relevant data related to a product, from its creation to its end-of-life and potential recycling, is easily accessible to various stakeholders such as manufacturers, consumers, recyclers, and regulators. Despite these benefits, the effectiveness of the DPP depends on the standardization of data formats for structuring and exchanging product information across industries and borders. However, the DPP is still under development, with boundaries set by legislation such as the ESPR, which came into force in mid-2024. Planned for implementation from 2026, the EU endorses the use of existing standards (page 12, [24]) such as the *Asset Administration Shell for Industrial Applications* [22] for the future standard of the DPP. In the present paper, we use the Asset Administration Shell (AAS) and its standardized metamodel for the implementation of a content-flexible DPP. The AAS, as outlined by the Platform Industry 4.0, serves as a digital representation of an asset and can provide the foundation for a "digital twin." However, its functionalities go beyond pure asset representation and enable proactive interactions and self-determined communications through embedded logic. This logic, which relies on asset-specific information and data, can trigger events such as asset or stakeholder-specific actions within Cyber-Physical-Social Systems (CPSS), as shown in Figure 1. This proactive behavior allows for scalable and dynamic exchanges, adapting to specific requests and responses in both local and global IoTs. Thus, the AAS is not the DPP itself, but a shell that encloses the DPP and

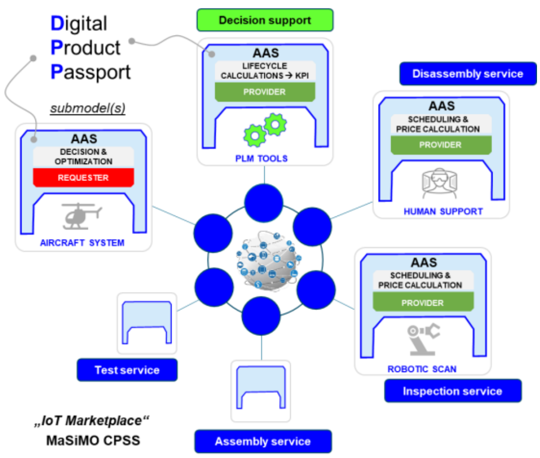

Figure 1: Interacting assets in the IoT that exchange DPP elements of interest

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enables it with a standard communication structure and interfaces, as well as server functionalities for seamless, even self-managed, exchange on request or event. This corresponds with the distinction between the DPPs themselves and DPP systems: "*The DPP is the artifact consisting of the data/information provided by the interacting stakeholders of a product's value chain. The DPP system is the underlying IT/software system that enables the consolidation of the data required for DPPs […]"* [38]. In the present paper, the focus shifts toward the latter aspect, building upon the overarching research question addressed in our previous work [56]:

RQ 1 How can the Asset Administration Shell be used, adapted or extended to be applied in data-driven MRO in the aviation sector?

This paper will then deepen this exploration by exploring the following question:

RQ 2 How can the AAS support a low-barrier implementation of a content-flexible DPP?

Building on our research presented in [53] [55] [56] [58] and taking into account the latest developments of I4.0, this paper describes the preliminary design of a DPP manager as an embedded part of a proactive AAS. To this end, the general concept of a DPP is introduced with findings from a literature review in terms of DPP's enablers, challenges and contents. The developed parts to advance the proactive AAS with the DPP and its elements are then described, followed by the presentation of its experimental application: An aircraft surrogate on the service requester side and a robotic system on the service provider side are used to simulate the interaction of assets in an MRO CPSS with data exchange on common ground. The exchange is based on the VDI 2193 standard ([51], [52]) for structured messages and interaction protocols as a language for I4.0 components.

2. DIGITAL PRODUCT PASSPORT

2.1. Enabler and Challenges

In response to the global shift towards electromobility as part of efforts to combat climate change, which is currently reflected in the fast-growing number of electric cars by 35 % per year (2023) [25], the production of batteries and their maintenance is increasing rapidly. However, this increase raises significant environmental concerns, such as resource depletion, pollution from manufacturing, and challenges related to waste management. Economically, it impacts value and supply chains by increasing costs associated with raw material sourcing, production processes, and end-of-life disposal or recycling. To address these challenges, the EU's new battery regulation will require manufacturers of electric vehicle batteries to provide a Battery Passport (BP). This BP contains essential information on the battery's composition, performance, recyclability, and carbon footprint, with the aim of improving recycling rates and reducing environmental impacts [47], and is maintained by all stakeholders throughout its entire life. Batteries are the first product at European level for which a Digital Product Passport (DPP) will be mandatory. The overarching reasons for implementing DPP are therefore as follows:

1. **Support for the Circular Economy**: The DPP is an important tool in fostering the circular economy, where products are designed and managed to be reused, maintained, or recycled. By storing detailed information on how a product can be recycled, repaired or disassembled, the DPP can ensure that fewer materials end up in landfills and more are recirculated back into the production process.
2. **Transparency**: One of the main functions of a DPP is to provide transparency about a product's composition, origin, production process, and environmental impact. This is crucial for industries where tracking materials is essential, such as electronics, textiles, and transport industries. It helps consumers and businesses make informed decisions and strengthens confidence in the sustainability of products
3. **Traceability**: The DPP enables traceability throughout a product's entire lifecycle, from raw material sourcing to end-of-life recycling. This is essential for ensuring that all components, such as those used in batteries, can be traced back to their origin, improving accountability across the supply chain. By enabling traceability, the DPP ensures that materials are sourced ethically, helps identify inefficiencies or risks in the supply chain, e.g. early warnings of shortcomings, and facilitates the efficient recycling or disposal of products.
4. **Compliance and Regulation**: The DPP helps companies comply with various environmental and safety regulations by ensuring that they meet requirements for documentation and reporting. It centralizes all required data, which can be shared with authorities or other stakeholders, making it easier to demonstrate compliance with laws regarding product safety, materials used, and sustainability.

However, there are a number of challenges associated with the implementation of the DPP, some of which are listed below and the first of which will be discussed later in relation to RQ 2:

1. **Standardization**: For DPPs to be effective, a standardized format for structuring and sharing asset data across industries and borders is essential. Developing these standards will require extensive cooperation among industries, governments, and international organizations. The current lack of a comprehensive, universally accepted framework for DPPs is a significant obstacle as conclude by several studies [46]. In this context, [39] identified seven data clusters for a common DPP framework from existing studies and reports: (1) usage and maintenance, (2) product identification, (3) product and materials, (4) guidelines and manuals, (5) supply chain and reverse logistics, (6) environmental data and (7) compliance.
2. **Information Gaps, Data Integration** and **Integrity**: Despite the DPP's role in supporting circular economy practices by providing detailed lifecycle data, significant information gaps among stakeholders can delay an effective implementation. Incomplete or inaccurate data makes it difficult to ensure comprehensive product tracking and lifecycle management. In addition, the integration of different data sources into a consistent DPP is challenging as stakeholders need to harmonize and manage information from different systems and formats [42], [44].
3. **Organizational** and **Technical Barriers**: Implementing DPPs involves overcoming organizational and technical challenges [7]. Organizations may need to adapt their processes and invest in new technologies to effectively integrate and utilize DPPs. This may involve substantial changes to existing workflows and systems. Additionally, technical challenges related to data security, interoperability, and the development of user-friendly interfaces must be addressed to facilitate smooth

adoption and utilization of DPPs. Another key challenge is to ensure equitable access to data. This includes defining who has the right to access specific types of information within the DPP and ensuring that this access is managed in a way that supports transparency and compliance without compromising data security. Balancing the need for broad access to information with the protection of sensitive data and respect for privacy concerns is critical to an effective DPP implementation.

4. **Economic** and **Incentive Issues**: Economic challenges include the costs associated with developing, implementing, and maintaining DPP systems [7]. Companies may require incentives to adopt DPPs widely, which could involve subsidies, grants, or other forms of financial support [2]. Thus, developing effective incentive structures is crucial to encourage widespread adoption and to ensure that the benefits of DPPs outweigh the costs for manufacturers and other stakeholders.

2.2. DPP content

The content of a DPP serves as the basis for enabling transparency, traceability, and sustainability throughout a product's lifecycle. In general, a DPP consolidates a wide range of data that reflects the product's characteristics, performance, and environmental impact. However, the specific content of a DPP may vary depending on the type of product and its intended application. This chapter first outlines the content common to most DPP concepts and then gives an overview of the use case specific content, referring to industry examples and legal requirements.

2.2.1. General Content: Required vs. Optional

Related to one of the latest systematic literature reviews on the anatomy of DPPs [50], it is clear that most concepts include general data areas aimed at ensuring consistent and comprehensive product documentation throughout the product lifecycle. While these data areas are essential for effective documentation, it is important to note that not all elements are mandatory; the only requirement for the initial setup is a product identification. The general content can be structured as follows:

1. **Identification** (required): Each DPP begins with unique asset identifiers such as a serial number and manufacturer reference. Barcodes or QR codes may be used to direct the user to the information stored in a DPP.
2. **Physical Composition** and **Technical Descriptions**: It refers to a bill of materials (BoM) and comprises technical documents such as drawings, guidelines or even a bill of processes (BoP). It contains the materials used in the product, their origin, chemical composition, and technical performance metrics, providing a thorough understanding of the product's construction.
3. **Lifecycle data** (inventory and impact): This covers the history of the product, including manufacturing, use and maintenance records. With the current focus on environmental performance, DPPs often include data on carbon footprint, energy consumption during production and recyclability, which are key to assessing and supporting the sustainability of the product.
4. **Compliance** and **Certification**: The DPP stores information on regulatory compliance, certifications, and safety standards to ensure adherence to legal and environmental requirements.

In accordance to the findings of a complementary review [46], these key areas can be expanded by introducing seven distinct generic data type categories, each corresponding to different stages of the product's lifecycle:

a. **Material Data**: Aligns with Physical Composition and Technical Specifications by detailing the types and quantities of materials used. This data is essential for understanding the product's composition and facilitating its recycling.
b. **Environmental Data**: Corresponds to Environmental Performance by including information about the environmental impact of the materials and manufacturing processes.
c. **Manufacturing Data**: This refers to information generated during the product's manufacturing process, including sensor data and machine reports. This data provides detailed insights into the production methods and performance of the product, helping to assess quality and efficiency.
d. **Value Network Data**: Covers information from the entire value network, including logistics and product tracking. This data ties into Lifecycle Data by documenting the product's path through the supply chain.
e. **Maintenance Data**: Records all maintenance activities performed on the product, providing a complete history of the product's use and MRO activities.
f. **Circularity Data**: Focuses on the implementation of circular economy practices, such as product reuse and recycling.
g. **End User Data**: Includes information generated by the product's use and interactions with the end user, such as instructions and maintenance requirements.

The previous analyses focus on scientific literature, with the contributions from the European CIRPASS project [40] more or less implemented. As CIRPASS is recognized for its comprehensive approach to developing a DPP information system in Europe, first in the sectors consumer electronics, textiles and batteries, it is worth looking at it separately. Its structured methodology provides a roadmap for the implementation of the ESPR requirements with recommendations for

- DPP information requirements,
- DPP system architecture and
- DPP supporting standards.

The results of CIRPASS-1 are published in four reports, namely "Identification schemes" [3], "DPP user stories" [1], "DPP System Architecture" [57] and "DPP Prototypes" [6]. These documents outline a framework for the distributed use of Digital Product Passports (DPPs), focusing on decentralized data storage, unique product and operator identifiers registered in an EU register, and embedded data carriers (e.g., RFID, barcodes). They emphasize top-level requirements and specifications aligned with the EU's Eco-Design for Sustainable Products Regulation (ESPR) [48], rather than specific technical implementations. While the specific details for various product groups will be defined in legal acts, the ESPR outlines general content requirements in Article 7 and Annex III. Key points include:

1. Content of general requirements

- **Unique identifiers** (products, stakeholders)
- **Global Trade Identification Number**
- **Compliance Documentation**
  - Declaration of Conformity: Certification that the product meets relevant standards.
  - Conformity Certificates: Official certificates verifying adherence to specific regulations.
- **Technical Documentation**
  - Detailed information on the product's design, function and performance limitations.

- **Operator/User Documentation**
  - Manuals and Instructions: Guides on how to use, install, maintain, and repair the product.
  - Warnings and Safety Information: Essential safety guidelines to ensure safe usage.
  - Environmental Impact Guidelines: Information on minimizing the product's environmental impact and ensuring durability.
- **Treatment Facility Documentation**
  - Disassembly Instructions: Guidelines for dismantling the product.
  - Recycling and Disposal Information: Procedures for recycling or disposing of the product at end-of-life.
- **Performance of the product** in relation to the product parameters (data record)

2. General Content of delegated acts

- **Data carrier**: RFID, Barcode etc.
- **Granularity level**: model, batch or item
- **Authorizations**: Who has access to which information, who is allowed to update what.
- **DPP availability**: At least the expected lifetime of a specific product

The synthesis of the previous findings can be translated into a basic DPP concept that includes both general categories and detailed data types that are essential for complete product documentation throughout the life cycle. While [50] emphasizes general components such as product identification or environmental performance, these have been detailed in [46] through specific data categories such as material data, which expand on physical composition, and environmental data, which provide deeper insights into environmental impacts. In addition, the data categories in [46] provide a deeper granularity of lifecycle perspectives compared to [50] and include aspects of production, maintenance and end-of-life processes. In combination with the EU regulations (ESPR) [48] and the corresponding CIRPASS results, we derive a generalized DPP as shown in Figure 2: It is based on the four pillars of nameplate, documents, life cycle data and certificates, each of which contains specific subdivisions in terms of required content. In addition, the structure must contain discrete time layers to enable the storage of all required data over the entire life.

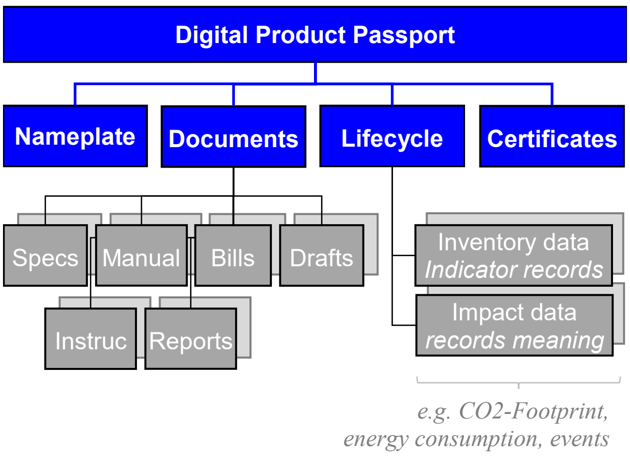


Figure 2: Generalized DPP, derived from [46], [50]

2.2.2. Specific Content

While the general content in Chapter 2.2.1 provides the basic anatomy of a DPP, specific stakeholders, asset types and sectors require additional customized information. These use-case specific details are tailored to the product's context and objectives [50]. To derive use-case specific content for a DPP in a technical framework, a structured approach involving data modeling, regulatory compliance, and stakeholder requirements is needed. Although there is no unique procedure for deriving an initial list of key data, two common steps can be identified across the different initiatives, e.g. in [54]:

Step 1: Identify Requirements

- **Objective**:
  - Define the product group and the relevant regulations (e.g., ESPR, EU Battery Regulation, etc.).
- **Stakeholders**:
  - Identify all stakeholders involved: Regulators, value chain participants, other industry participants,
- **Process**:
  - Describe Product: Describe the specific product value and process chain and its lifecycle phases.
  - Review Regulatory Requirements: cross-sectorial (e.g. REACH, ESPR) and specific regulation (e.g. RoHS, Battery Regulation, WEEE)
  - Stakeholder Consultations: Engage regulators and industry bodies for input on necessary standards and metrics (e.g., recyclability, durability).

Step 2: Define Key Indicators and **Data Sources**

- **Objective**:
  - Translate regulatory requirements into specific, measurable indicators.
- **Stakeholders**:
  - Select specific participants from the identified stakeholders such as technical experts, manufacturers (e.g., production teams, compliance officers), service providers or third-party certifiers (e.g., compliance auditors, standard bodies).
- **Process**:
  - Derive Impact Indicators: Based on the regulations, if available, define product-specific indicators that measure the outcomes of the product's lifecycle such as durability (lifespan), reusability (modular components), recyclability (% of recoverable materials), carbon footprint, or depletion potential.
  - Derive Inventory Indicators: Define detailed characteristics and component-specific properties for the calculation of impact indicators
  - Map Data Sources: Identify where the data for each indicator will come from (e.g., lifecycle analysis reports, manufacturer data, IoT devices, third-party audits → Step 1: value/process chain).
  - Select Data Formats: Ensure data is standardized (e.g., JSON, XML) for easy integration into DPP platforms.

For the efficient creation of a Digital Product Passport (DPP), leveraging existing regulations, directives, and delegated acts is crucial. While the EU Strategy for Sustainable Products Regulation (ESPR) provides a comprehensive framework that sets the cross-sectoral basis for the future of product passports, its content will be further specified in delegated acts that tailor these regulations to specific product groups: For instance, the Battery Regulation 2023/1542 [47] and Battery Directive 2006/66/EC provide specific requirements for the production, use and waste of batteries, including recyclability, energy storage capacity, and the presence of hazardous substances. Similarly, the Construction Regulation Proposal [45] outlines ecodesign criteria for construction products, focusing on durability, reparability, and resource efficiency. The Ecodesign Directive 2009/125/EC sets general standards for the environmental performance of products, influencing indicators such as energy efficiency and waste generation. Furthermore, the Energy Labelling Regulation (EU) 2017/1369 mandates energy efficiency labeling, impacting indicators related to energy consumption and performance. The RoHS Directive 2011/65/EU restricts hazardous substances, guiding indicators on material safety. The WEEE Directive 2012/19/EU addresses waste management and recycling, influencing indicators on the recyclability and recovery of materials.

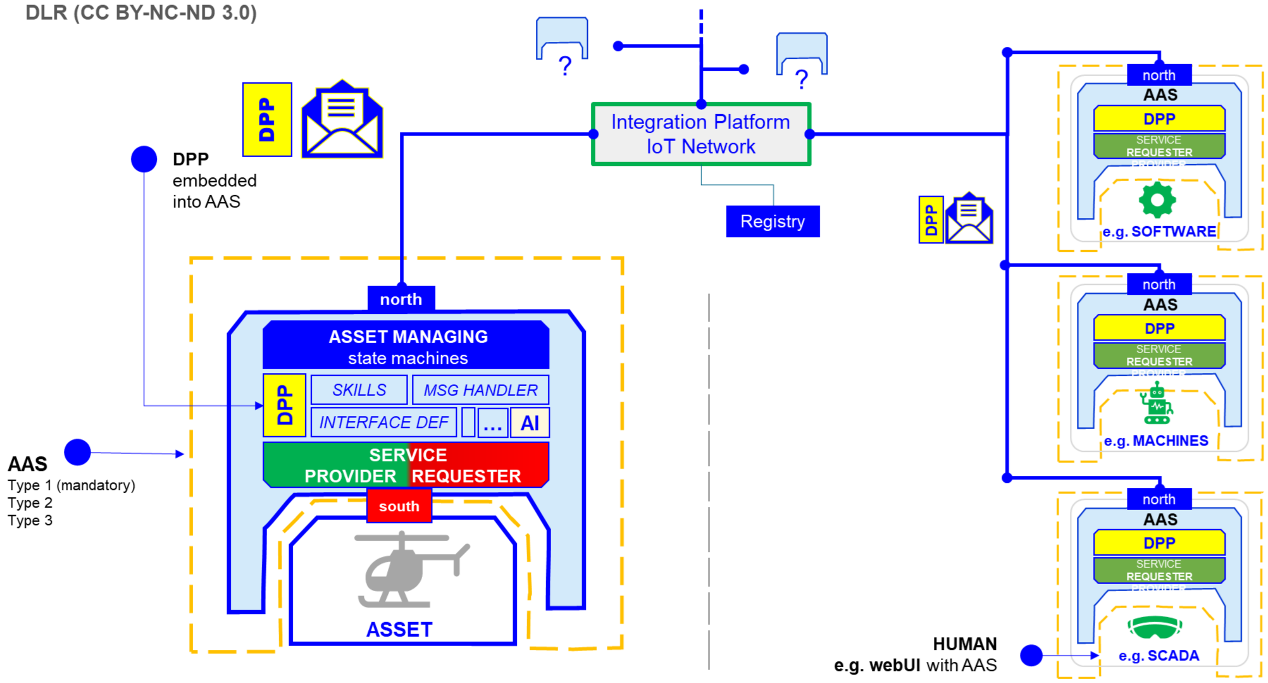
By initializing a DPP with these existing regulations, it ensures that the passport is not only compliant but also tailored to the specific needs of different product categories. This approach facilitates the inclusion of relevant indicators, such as those for durability, repairability, recyclability, performance and environmental impact, which are critical for supporting sustainable product management and circular economy practices across various sectors. An example set of data indicators can be derived from the requirements of the previous regulations for creating the specific content of a DPP for a generic product, as illustrated in Table 1. These indicators are clustered in accordance with the suggestions of the Battery Passport Group, namely Labels and Certifications, Carbon Footprint, Materials and Composition, Circularity & Resource Efficiency, and Performance & Durability.

3. DPP IN PROACTIVE AAS

The Digital Product Passport (DPP), as introduced in chapter 2, first describes the properties of an asset over its lifecycle so that all partners can understand and correctly interpret the content (semantics, unified ID etc.). But in order to use the DPP in an operational IoT environment, it needs to be equipped with a standardized interface and communication framework. In this context we propose in [56] and [55] the fundamentals of a CPSS of a data-driven maintenance environment. It consists of data networks and proactive Asset Administration Shells (AAS) as interacting components. The AAS is defined by the Plattform Industry 4.0 [21] as a standardized digital representation of an asset ("digital twin") to make it available in digital data spaces (DIN EN IEC 63278-1 [22]). As presented in [55], we build-up on Python-based proactive AAS to create Industry 4.0 components (I4.0C) for an exemplary data-driven MRO environment (requester/provider) with self-managed interactions in terms of service requests and provisioning based on a bidding protocol and logics of decision-making. Here

Table 1: Example of a derived set of data indicators related to the specific content of a DPP

Category	Requirement	Indicator	Application for a Generic Product
Labels and Certifications	Compliance with Standards	Certifications (ISO, CE, etc.)	Ensure compliance with industry standards (e.g., ISO 9001 for quality, CE marking for safety).
	Repairability	Repairability Score (0-10)	Rate the product based on ease of repair (spare parts availability, manuals, etc.).
	Hazardous Materials Compliance	RoHS/REACH compliance	Verify product for restricted substances according to RoHS or REACH directives.
	Energy Labeling	Energy Efficiency Rating (A++ to D)	Compliance with Energy Labelling Regulation (EU) 2017/1369 for energy efficiency labeling.
Carbon Footprint	CO_2 Emissions	Carbon Footprint (kg CO_2 equivalent)	Measure and report the total carbon emissions during the production and operational phases.
Materials and Composition	Material Composition	Percentage of Recyclable Materials	Identify the percentage of recyclable materials such as metals, plastics, etc., used in the product.
	Presence of Hazardous Materials	Restricted substances	Identify any substances restricted by EU regulations such as RoHS or REACH.
	Recycled Content	Recycled Material Percentage	Calculate the percentage of recycled materials used in the product's manufacturing.
Circularity & Resource Efficiency	Recyclability	Recyclability Rate (%)	Measure the percentage of materials that can be recovered at the product's end-of-life.
	Reusability	Modularity and Reusability	Assess if components can be reused in other products or refurbished after disassembly.
	Expected Waste Generation Energy Recovery	Amount of Non-Recyclable Waste (kg) Potential for Energy Recovery	Estimate the amount of non-recyclable waste generated at the end of the product's life cycle. Evaluate the potential for recovering energy from the product at the end of its life
Performance & Durability	Durability	Expected Product Lifespan (years)	Estimate the expected lifespan of the product under standard operating conditions.
	Performance Degradation	Performance Degradation Over Time (%)	Measure how much the product's performance decreases over its lifespan
	Maintenance Requirements	Maintenance Frequency (ops vs. maint. hours)	Specify how often maintenance is required to ensure optimal product performance.
	Repairability	Availability of Spare Parts (Y/N)	Indicate whether spare parts for the product are readily available for repairs.
	Efficiency	Operational Efficiency	Measure the product's efficiency, such as energy consumption per unit of operation



a. AAS with their components plus DPP | b. Participants interacting in the IoT

Figure 3: Interoperating AAS in an experimental data-driven MRO environment, e.g. with exchange of DPPs

we want to extent this AAS framework with functionalities to design and manage DPPs and Events in regards to the AAS' corresponding asset. The Asset Administration Shell provides the standardized meta-model in which the DPP can be nested as an additional feature, utilized by the previous mentioned Python-based framework. Using the AAS as a wrapper around a DPP, we refer strongly to the developments of the DPP4.0 [23], with taking other ideas such as in [44] into account. Thus, we don't develop the meta-model of the DPP itself, but use already revised schemas and extend them with a framework for common communication, including self-managed behaviour and a WebUI for low-barrier customization of the DPP.

3.1. Basic Framework

The AAS enables interoperability and supports passive, reactive and proactive scenarios. The main goal is to enable a seamless data exchange between different stakeholders with different in-house technologies or applications, as illustrated in Figure 3, which also represents a CPSS in our MRO research environment called **Industry 4.0 Plateau**: The AAS, as a common "plug" at the application layer, ensures uniformity and enables the exchange of the DPP in a format agreed by all stakeholders. Furthermore, the evolution of the AAS to Type 3, the proactive type (Figure 3 a.), enables operations with autonomous entities acting as both self-managed service providers and requesters. For example, an "AAS PLM Software" can autonomously request DPP data from an "AAS Robotic Service" or an "AAS Human Interface" (involvement of humans) and vice versa (Figure 3 b.). This illustrates the potential for highly developed interactions that pave the way for decentralized CPSSs within a common dataspace. This strategic approach not only streamlines communication, but also enhances operational autonomy and efficiency across multiple stakeholders. To achieve this, our proactive AAS integrates various components that collectively represent the asset. This includes modules for internal data flow management, state machines, smart decision algorithms, and standardized interfaces, all of which facilitate the management of digitally available identifications, documents, certificates, BoP, BoM, CAD files, and the execution of specific actions. Practically, the AAS has been designed in such a way that it enables seamless connections both northbound (from the AAS to the IT network) and southbound (from the AAS to its asset) and thus provides the DPP with a common communication framework using protocols such as HTTP, REST, OPC UA or MQTT. As we introduce in [55], all of this is managed by a complex server system, which is further extended with a module to manage Digital Product Passport(s) within the proactive AAS.

As the AAS and its AASX file, an I4.0 standardized package format that stores the data and information of the AAS, represent a kind of "Digital Twin," an integrated Digital Product Passport (DPP) becomes more valuable and provides a comprehensive view of the asset. The focus on creating an AASX package file for DPP integration also extends to the wider value chain and LCA. The AASX, enriched with DPP submodels, forms the basis for PLM applications that optimizes both production and service processes and the product itself throughout its life cycle, taking CE into account. The application of "AAS+DPP" aims to enhance socio-eco-efficiency by supplying essential information that enables users to minimize environmental impact, maximize resource efficiency, and improve social implications, depending on their specific objectives.

3.2. DPP extensions of the AAS framework

In principle, the DPP in the AAS is a flexible set of AAS submodels with unique semantic ID, here managed and made accessible by the Python-based AAS server system. With reference to Figure 2, the submodels group at the top the required DPP key areas such as asset identification, documentation, lifecycle data or certificates, where submodel element collections (SMCs) sub-group the required product characteristics (e.g. product durability and reliability, reparability, maintenance, presence of substances of concern, etc.). Submodel elements are used to implement the measurable data properties (incl. Boolean) within each DPP group.

To systematically structure the general implementation of the DPP within the AAS framework, we first construct an overarching submodel called the DPP Container, as illustrated in Figure 4. This container is designed to store multiple DPPs for design purposes, with each DPP represented by a *SubmodelElementList* (SML). The SML stores different submodels by their semantic IDs, ensuring system-independent identification and facilitating cross-platform interoperability. This structural design allows each component to be easily managed, extended and queried within the DPP. An important property of the *DPPcontainer* is the *masterDPPidShort*: the master DPP is the only valid instance for real-world asset interactions in production or operation, while other “DPP SMLs” are retained for design and validation purposes only. In Figure 4, DPP2 is set to master as an example, which is redundantly indicated by the qualifier "primary=true" of the affected SML. Thus, the qualifier also retains the information with the SML, which should avoid inconsistency in the case of import/export activities.

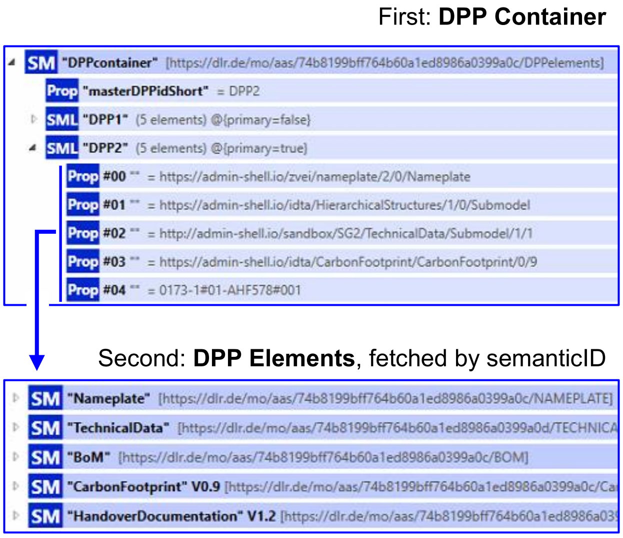


Figure 4: DPPcontainer and relation to content SMs

3.2.1. Back- and front-end architecture

The DPP has been implemented as an extension to the Python AAS framework, enhancing both the back-end (server) and front-end components. This approach will ensure that the DPP integrates seamlessly with the existing functionality of the proactive AAS and its repository, while extending its capabilities to meet specific requirements for the management and presentation of the DPP. The backend is designed to handle HTTP/REST requests, manage server-side logic and ensure compliance with AAS interfaces. The front-end, which includes the WebUI, serves as a visual interface for user interaction, rendering web pages and making REST requests to the back-end. This architecture supports both technology-neutral approaches and technology-specific implementations in line with Industry 4.0 compliance.

3.2.1.1. DPP back-end (server)

The **primary** functionalities provided on the server-side include:

- **AAS submodel management**: The data server provides and manages submodels based on their identifications if they are instantiated in the AAS repository. The extended AASWebInterfaceDPP class organizes them in the DPP container submodel. The class processes data at runtime level and ensures that all interactions are valid and correspond to the AAS interface patterns, e.g. **GET**, **POST** operations.
- **Compliance with AAS API Specifications**: The server-side architecture ensures compliance with I4.0-defined APIs and service operations, providing technology-specific implementations via HTTP/REST interfaces. This includes the implementation of standardised AAS interface terminology such as GetSubmodelsBySemanticId and GetSubmodelElementByPath_SRI.
- **Service Instantiation and API Operations**: The server instantiates service implementations and API operations according to the Industry 4.0 model. Each operation, such as creating, updating, or deleting submodel elements, is encapsulated in an API-operation instance. The server is also designed to handle nested submodels like Bill of Materials (BoM), which require recursive and hierarchical data access patterns.
- **Asset’s real data mapping**:
  As we introduce in [55], the AAS server uses various interfaces to interact with its asset such as OPC UA or REST. The fetched data can be mapped to properties within the DPP submodel(s) using hierarchical paths referred to as *idShortPath* in Figure 5: These paths link the asset real-time data with the corresponding properties within the DPP and enable their real-time processing and visualisation. Additonally, the server records the real-time data upon events, with options for storing this data either internally within the DPP submodel(s) or externally in referenced databases.

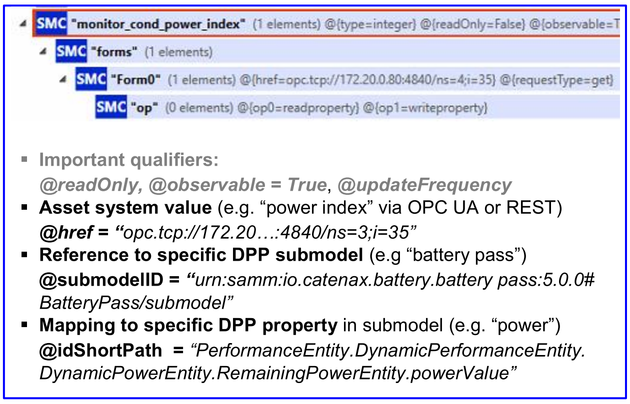


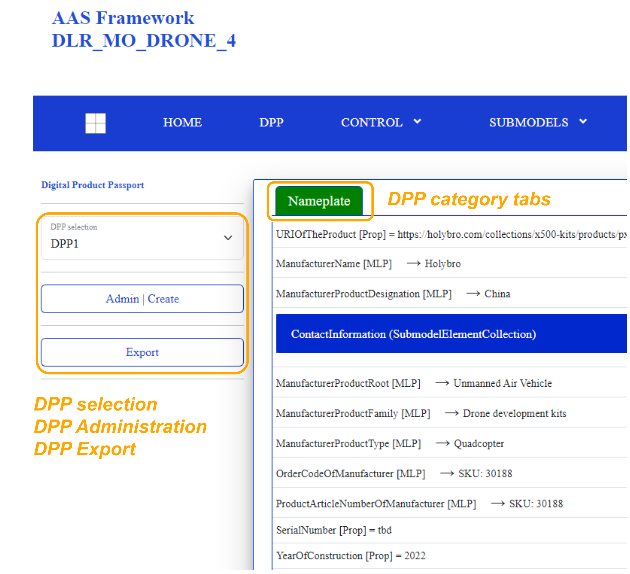
Figure 5: SM asset access definition

The **secondary** functionalities provided by the added AASWebInterfaceDPP class include:

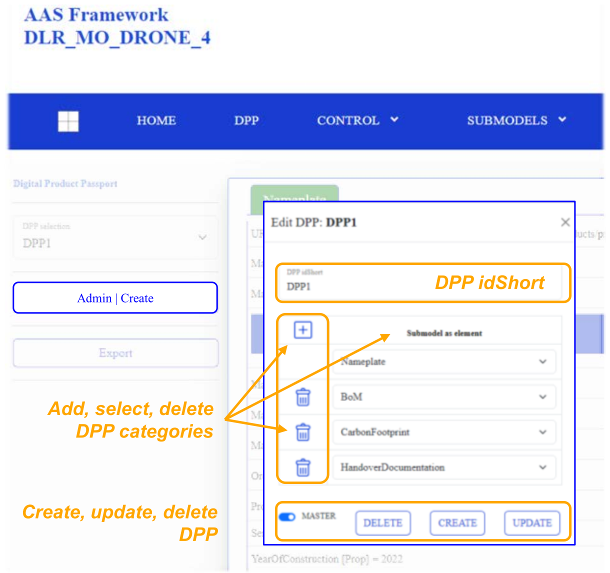
- **DPP Submodel Management**: The class manages the DPPContainer submodel, allowing dynamic creation, modification, and deletion of DPP submodel sets in terms of lists (SML) their semanticIds of the “Content” submodels, for example:

  IDTA Nameplate → Identification, general information
  ID: https://admin-shell.io/zvei/nameplate/2/0/Nameplate

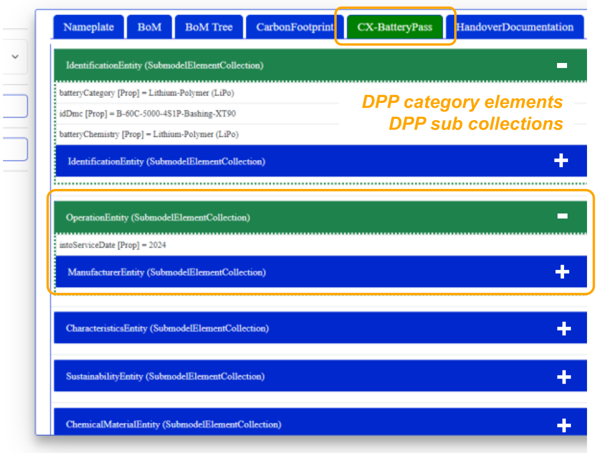
- **DPP Master Handling**: Through the masterDPPidShort property, the system ensures that only one



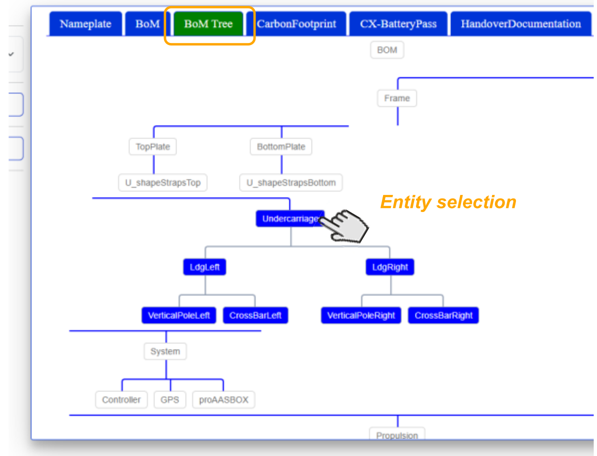
a. Main page of DPP displaying the Nameplate category



b. Admin window for adding and removing categories



c. DPP tabs showing five categories with e.g. the BatteryPass tab active and its sub menu expanded



d. BoM Tree tab active, visualizing the hierarchical composition of the asset

Figure 6: WebUI of the DPP, provided by the AAS server

DPP SML is marked as the "master," simplifying the management of multiple DPPs in the design stage.

- **Validation**: The class validates input from the WebUI, e.g. checking for correct idShort formatting (alphanumeric, no special characters), preventing duplicate submodel identifiers or deletion the master.
- **Database Operations and AAS Interface Descriptions**: Embedded within the overarching AAS framework, the developed AASWebInterfaceDPP interacts with server elements and the database to perform CRUD operations on the DPPContainer submodel. The DPP embedded submodels (e.g. Nameplate) are managed separately, either via the corresponding "Submodel" WebUI or directly via REST interface, always using I4.0 interface terminology such as

/shells/{aas-identifier}/submodels/{submodel-identifier}

3.2.1.2. DPP front-end (WebUI)

The WebUI is tightly integrated with the server, providing an additional interactive interface that complements the technical functions exposed by the Python AAS framework (Figure 6). The WebUI supports the management and visualization of the Digital Product Passport using a combination of **Bootstrap** for layout, **JavaScript** for client-side interaction and **Jinja2** for dynamic content rendering. An initial data loading strategy ensures that all relevant submodel data is available upon opening, enabling a seamless usage. The developed WebUI includes the following key features:

- **Initial Data Loading and Representation**: At the initial page load, the WebUI fetches and renders all relevant submodel data from the AAS repository. This data includes submodel identifiers, hierarchical structures, and associated elements. **Bootstrap** is utilized for layout and responsive design, ensuring that the user interface is consistently displayed across different devices. **Jinja2** templates facilitate the dynamic rendering of submodel data into HTML, which is then presented to the user in a structured format.
- **DPP Management** (Figure 6 a. and b.): Users can interact with the AAS repository through the WebUI, for adding or removing DPP content in terms of submodels from the SML, setting a new **master DPP**, renaming or deleting if not master. These forms are validated

both on the client side (using **JavaScript**) and server side, ensuring compliance with AAS data integrity rules.

- **Tab-Based and Accordion Submodel Visualization** (Figure 6 c.): Submodels within the DPP are displayed as individual tabs, each representing a different component of the Digital Product Passport, such as “Carbon Footprint” or a subordinate “Battery Pass”. This tab-based design is implemented using Bootstrap's tab components, which allow for clear separation of data and easy navigation between different DPP elements. The tabbed submodels themselves are visualised using Bootstrap's accordion component.
- **Visualization of Bill of Materials** (Figure 6 d.): The Bill of Materials (BoM), if available and based on the IDTA SM "Hierarchical Structures […]" [31], identified by its semantic ID, is visualized as a tree in a separate tab. It is rendered using JavaScript and CSS, which provide interactive features such as expand/collapse nodes, allowing users to effectively explore complex nested/hierarchical structures. In future versions, the nodes may contain more information or a direct link to a related component.

3.3. DPP content with aspect- and submodels

The submodels serve as modular representations of different product attributes, allowing the seamless integration of various data points. These submodels will cover essential regulatory aspects such as durability, recyclability, hazardous substances, and carbon footprint, and extend to more specific use-case data as required by law. Technically, the DPP can be composed of any JSON model that conforms to the submodel scheme of the AAS metamodel. However, in practice, the submodels used should firstly represent the mandatory general content as required by the regulations introduced in Chapter 2, and secondly incorporate use-case specific content, guided by sector-specific reuirements, such as those mandated by the EU battery regulations or other sectoral directives.

To support commonality, we focus on using published and officially approved submodels and, where necessary, creating new ones or adapting existing ones. Various stakeholders develop submodels or variants thereof, which are later mapped in submodels, some of which have already been validated against the AAS scheme and made openly available by the responsible IDTA on the following website (accessed on 11.09.2024):

https://industrialdigitaltwin.org/en/content-hub/submodels

In addition, the European Gaia-X and the complementary German Manufacturing-X initiative are fostering major projects to digitize value and supply chains: For example, the Aerospace-X project was launched in mid-2024 to initialize a data ecosystem for the aviation industry, taking into account the experiences and developments of the other X initiatives. In this context, CATENA-X is worth mentioning as an emerged ecosystem for the automotive industry, with its three pillars of association, development and operation: among other things, they define standards and develop so-called aspect models, whose content goes beyond environmental aspects to include, for example, quality, fleet or capacity content. They also make these available in the AAS-compliant submodel standard and organize them under the Eclipse-Tractus-X project (development pillar), where the models are maintained in an open source git repository:

https://github.com/eclipse-tractusx/sldt-semantic-models

A screening of the repositories offers an initial selection of submodels that align with the DPP content requirements outlined in Chaper 2. Table 2 categorizes these potential submodels in accordance to the clusters from Chapter 2.2.2 (Table 1). They are extended by the Documents section, which includes submodel examples for managing manuals, drafts, files, etc.

Table 2: Submodels for main DPP categories

Labels and Certification
Labels: ▪ IDTA 02006: Digital Nameplate [29] ▪ IDTA 02002: Contact Information [26] ▪ CX-0019: Serial Part [8] ▪ CX-0021: Batch [9] Certificates: ▪ CX-0112: Material Recycling Certificate [20] ▪ CX-0108: Waste Certificate [19] ▪ CX-0107: Reuse Certificate [18]
Carbon Footprint
▪ IDTA 02023: Carbon Footprint [36] ▪ CX-0026: Product Carbon Footprint [10]
Material and Composition
▪ IDTA 02034: Materials in ERP, PLM … [37] ▪ IDTA 02011: Hierarchical Structures … BoM [31]
Circularity & Resource Efficiency
▪ IDTA 02013: Reliability [32] ▪ IDTA 02014: Functional Safety [33] ▪ CX-0038: Fleet Diagnostic Data [13] ➔ see also certificates above + Carbon Footprint
Performance & Durability
▪ IDTA 02003: Frame for Technical Data [27] ▪ CX-0037: Vehicle Product Description [12] ▪ CX-0040: Part Analysis [14] ▪ CX-0041: Manufactured Parts Quality [15]
Documents
▪ IDTA 02004: Handover Documentation [28] ▪ IDTA 02010: Service Request Notification [30]

Complementing this separate view of models are compositions of them into a kind of passport for whole system units. While the IDTA has announced it (e.g. Battery Passport), CATENA-X, via Tractus-X, is already offering the first kits, e.g. for electric drive systems, from power supply through transformation to transmission, framed with a DPP:

- **CX-0034** **Battery** Pass [11]
- **CX-(tbd)** **Electric drive** Pass *(available in the git)*
- **CX-0095** **Transmission** Pass [16]
- **CX-0103** **Digital Product Pass** (Frame) [17]

Several other initiatives such as the Battery Passport Consortium[1], CIRPASS and its members, Mobi BatteryTRAK[2]

[1] https://thebatterypass.eu

[2] https://dlt.mobi/standards

or the European GS1[3] work in cooperation with the Global Battery Alliance (GBA)[4], as does CATENA-X, on passport concepts. As they are mostly based on the ESPR, the semantics are the same. For example, the Battery Passport Consortium provides a data model on its public git repository at

https://github.com/batterypass,

which covers the 6 categories in common to the aspects in Table 2, with the properties varying in granularity or designations. These passes and their corresponding submodels can also be assumed to be subordinate parts of a higher-level DPP of a system. However, they remain separately identifiable so that they can be detached from the higher-level system DPP with their associated component, such as a battery. Our framework supports the design of a DPP in this way, but also allows the creation of a higher-level AAS consisting of the AAS of each component with its own DPP. The DPP for the parent AAS would simply reference the other DPPs in the BoM.

4. EXPERIMENTAL VERIFICATION

In this chapter, the developed DPP implementation is applied to an aircraft system surrogate, based on the unmanned aerial vehicle (UAV) Holybro X500. As we describe in [55], this UAV was advanced to an Industry 4.0 component (I4.0C) by integrating a proAAS BOX – a hardware complement to the proactive AAS we create (see Figure 7, the part at the top of the aircraft). The surrogate works as both a service requester and a service provider within a maintenance, repair, and overhaul (MRO) IoT scenario. We want to build on this framework by applying the DPP to track and manage the UAV's key components via the proactive AAS, in particular the data of the overall asset plus its power system. As we are in a preliminary design stage, not all aspects of the passport or the passport system requirements are considered. First, we focus on the experimental verification of the developed DPP implementation. Secondly, we conceptualize the DPP for a dynamic system in order to investigate, in subsequent research tasks, both the technical implementation of digital product passports in I4.0C and the improvement of the autonomous interaction of assets in the IoT via DPP-equipped proactive AAS. For example, a common IoT capability of "DPP management" could be introduced, which is then realized through asset-specific skill implementations.

4.1. DPP implementation into I4.0 Component

The DPP of the I4.0C "UAV" is initialized with submodels that realize, at the top level, the nameplate for the category labelling, the bill of materials for the overall composition, a carbon footprint, technical data for general asset specification and a document container. These primary categories are extended with the integration of the Tractus-X Electric Drive Pass and Battery Pass V6.0.

For the BoM, the IDTA submodel template "Hierarchical Structures Enabling BoM" is added and customized according to the "full" archetype structure, encapsulating all components, including grouped items like screws, represented with the "BulkCount" property. In contrast to complex applications, the BoM is here built based on a hands-on systematic decomposition of the UAV: Thus, the "EntryNode" is designated as "Assembly," serving as the primary entry point into the hierarchical structure. From the EntryNode the BoM is subordinated into four identified construction clusters, with the child nodes being "Frame," "System," "Propulsion," and "Power" on a primary level, as shown partly in Figure 9 a.

Figure 7: Aircraft surrogate with proAAS BOX

The submodel organizes the hierarchical structure by self-managed and co-managed "Entity" *SubmodelElements* as nodes for each asset. Self-managed entities are represented by assets that have their own AAS, ensuring detailed management and tracking. In contrast, co-managed entities do not have their own AAS and are instead managed within the hierarchical context of the submodel. The differentiation between self-managed and co-managed entities is facilitated through the "entityType" attribute. For example, the four propulsion units of the UAV are assumed here to be self-managed entities, while their components, except the motors, are co-managed. The hierarchical relationships are represented using the "IsPartOf" relationship of the template to show the logical connections between assets and sub-assets and their nodes respectively. Exemplarily shown as BoM tree in Figure 9 b., the *electric drive one* in the prolusion cluster is defined with:

(Bottom) Motor_1 *IsPartOf* MotorBase_1
MotorBase_1 *IsPartOf* Propulsion_1
Propulsion_1 *IsPartOf* Propulsion
Propulsion *IsPartOf* Assembly (Top)

In this way, the full BoM for the UAV was created at the overall aircraft level, considering all the parts in Figure 8. Next, the Tractus-X Electric Drive Pass (EDP) is added to the DPP, with the intention to represent the UAV's electric propulsion system. Originally developed for automotive

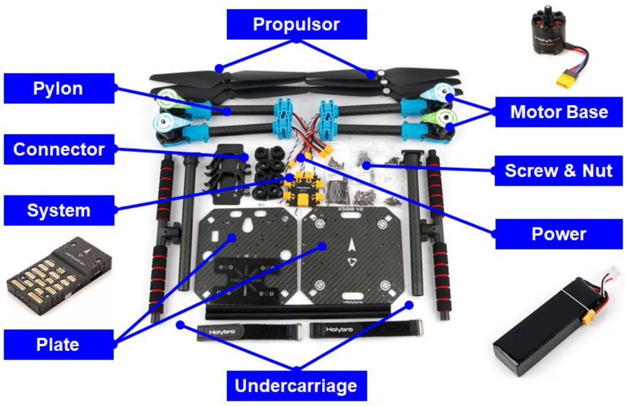
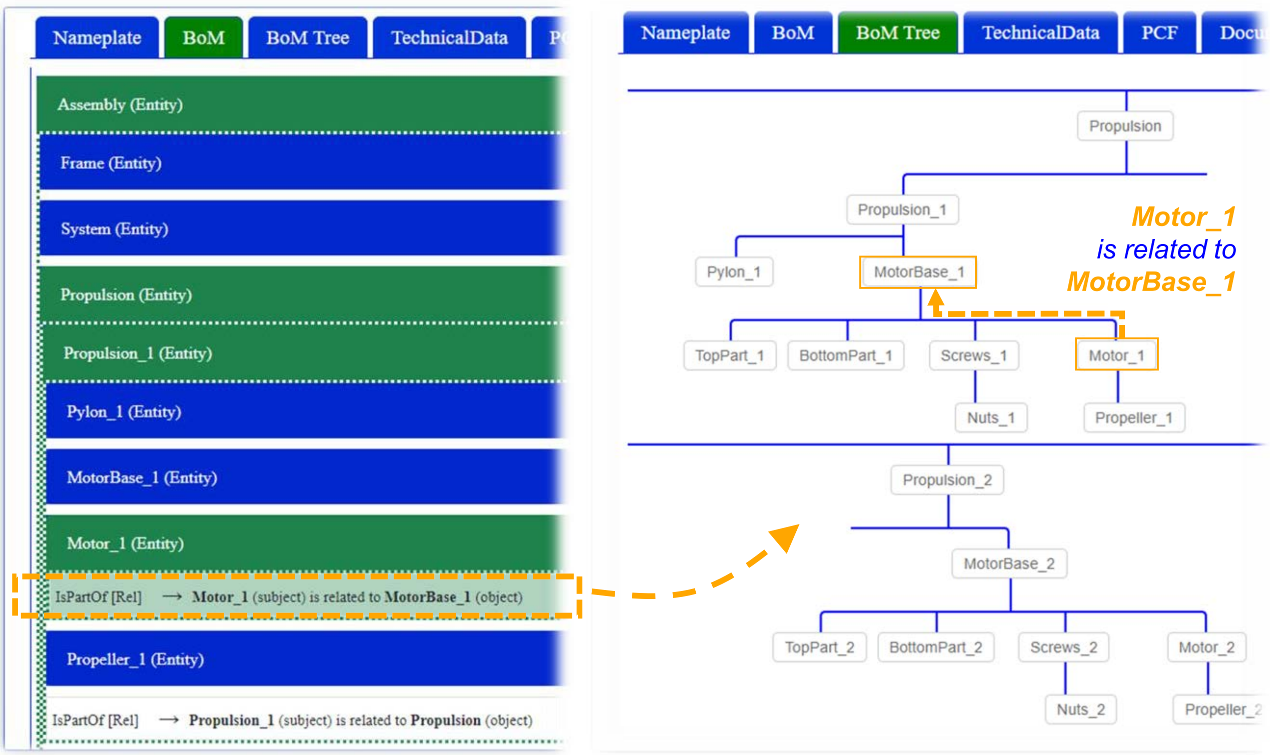


Figure 8: Decomposed UAV

[3] https://gs1.eu/activities/digital-product-passport

[4] https://www.globalbattery.org



a. AAS-DPP tab “BoM”

b. AAS-DPP tab “BoM Tree” for visualizing the BoM, highlighting the relationship between Motor_1 and MotorBase_1.

Figure 9: DPP BoM utilizing the submodel “Hierarchical Structures enabling Bills of Material” [31]

applications, the EDP framework covers the three main modules of electric drive systems: power electronics, transmission and electric motor. While these modules are common to both automotive and aviation sectors, their design and performance requirements differ significantly. In aviation, electric drive units must be optimized for higher power-to-weight ratios and handle more extreme environmental conditions, such as varying atmospheric pressures and temperatures. Furthermore, aviation applications often require more advanced cooling systems and redundancy measures due to the critical nature of flight operations. Despite these differences, the EDP provides a valuable starting point for integrating electric drive technology into aircraft, offering a foundational framework that can be further adapted and refined to meet the specific needs of this domain. Here, it is being used for the first time to address the DPP requirements in terms of UAVs.

Basically, the EDP is divided into a generic and a specific part as the reduced UML diagram in Figure 10 shows. The first part contains information about e.g. labelling, sustainability, manufacturer, operator or even a repairability score, as required by the ESPR. In the published AAS-compliant file, the specific part contains technical descriptions, including specific operating data and limitations or documents, separated by the *SubmodelElementCollections* (SMC) electric “EMachine”, “Inverter” and “Transmission” (see Figure 11). An SMC “System” contains the general power and torque data of the drive, while a SMC “Liquids” contains data on the pressure and temperature of the cooling and lubricating oil. The latter indicates the specific drive architecture, as our UAV drive is only air-cooled. While we won't explore every customization in detail, the EDP has been adapted to reflect the specific UAV propulsion system. An extract of the DPP, shown in Figure 11 as a blueprint example, details the "EMachineEntity" SMC. This extract includes key motor attributes such as the motor ID (AIR2216II-KV920), permanent magnet type (N45 SH), rated speed (9857 RPM), stator diameter (22 mm), and technology (Brushless DC Motor). The motor weighs 64 g and operates with 4S LiPo batteries (16 V), delivering peak performance with a power output of 272 W at 17 A.

To provide a deeper insight into performance under different conditions, we have extended the EDP with a performance map. As shown in Figure 10, this map is implemented by a *SubmodelElementList* (SML) “PerformanceMap” under the SMC "System", where each data point is listed by a single SMC. The latter bundles variables such as thrust, power, and efficiency at specific throttle settings that are related to each other at that specific point. The map covers throttle ranges from 30 % to 100 %, with thrust values from 210 g to 1332 g, power outputs from 23 W and 260 W, and efficiency levels ranging from 9.12 g/W to 5.13 g/W. This structured data enables a clear view of system performance under varying loads and supports performance optimization.

The EDP version used (V2.0) does not support the recording of real-time data series, which is another benefit of the DPP. As we will see later, the Catena-X Battery Passport, for example, distinguishes between rated and dynamic performance elements. The latter stores the value with its corresponding time stamp as a single record of various properties such as remaining power, voltage, current, temperature, etc. Therefore, to store time series in the EDP, either a kind of anatomy of the battery pass could be considered, or the existing “ElectricDriveDocuments” container in the EDP could be used to provide path references to datafiles of interest.

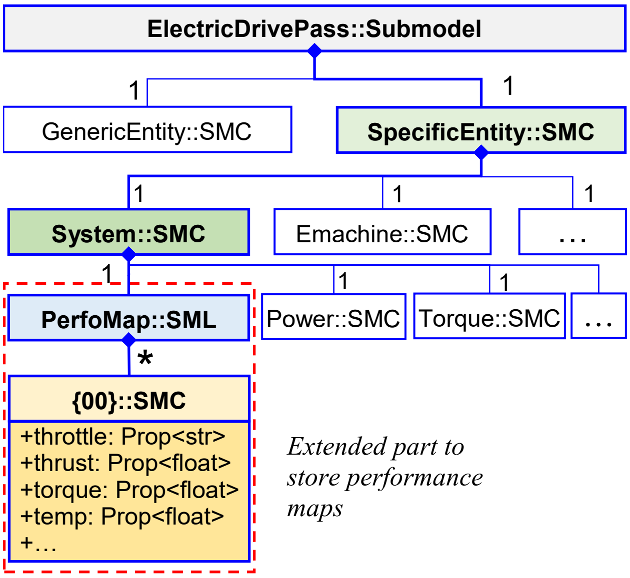


Figure 10: Reduced UML-Diagram of the Electric Drive Pass submodel, extended here by a performance map

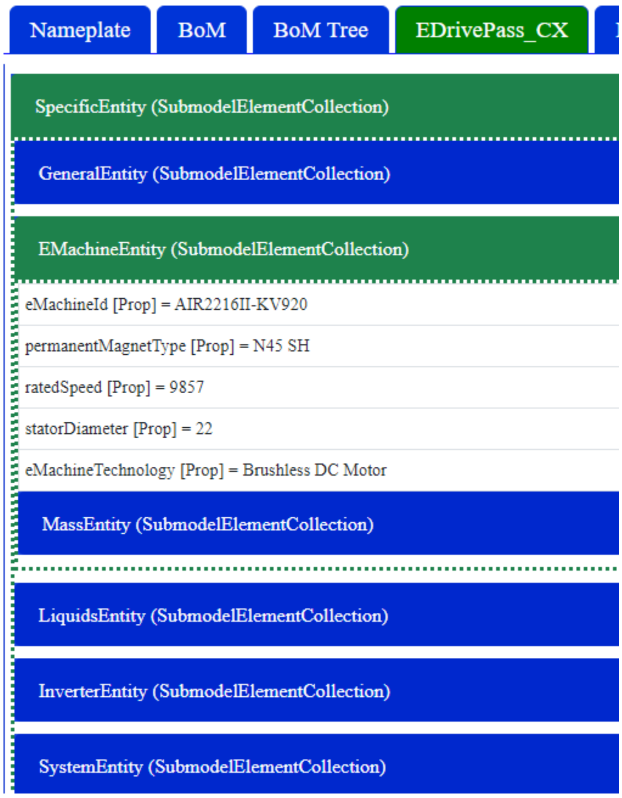


Figure 11: Extract from EDrivePass tab of the DPP

To represent the UAV's energy storage system, including technical specifications and chemical composition, we added the Catena-X Battery Passport submodel in the DPP. The version used aligns with Battery Passport Data Model 6.0.0, which encompasses several key categories. The categories are represented by SMCs as illustrated in the reduced UML in Figure 12. While we won't go into every detail, we will summarize strongly the content of the rated data and focus on the dynamic part in terms of real-time data recording.

- **Identification**: Including typology (LiPo 4S) and unique ident (B-60C-5000-4S1P-Bashing-XT90).
- **Sustainability**: Captures data related to the carbon footprint, recycled materials, and sustainability documentation, ensuring a responsible supply chain and end-of-life treatment.
- **Chemical Materials**: This includes critical elements like Lithium Cobalt Oxide ($LiCoO_2$), Graphite (C), and Lithium Hexafluorophosphate ($LiPF_6$), with percentages normalized to ensure they total 100%.
- **Performance**: Detailed performance characteristics of the battery, such as 14.8 V, 5000 mAh capacity, and 35C electrical load, along with dynamic values obtained through real-time operation.
- **Conformity**: Legal and regulatory compliance data.
- **Safety**: Safety information relevant for the battery's usage and transportation.

As highlighted in Figure 12, the dynamic characteristics of the UAV's power system are stored in SMCs, each for power, capacity, cycles, energy, round trips, internal resistance or even the negative event documentation. A data set is represented by an SMC itself (e.g. "Remaining-Power"), and the real-time data is mapped directly to it (see Chapter 3.2.1.1). To record its time series, either a new SMC is created for each data point, or an SMC or SML is created to store the properties of the data points in a list. Another approach is to store the data points in time series files and link them to a designated "file" submodel element under an SMC.

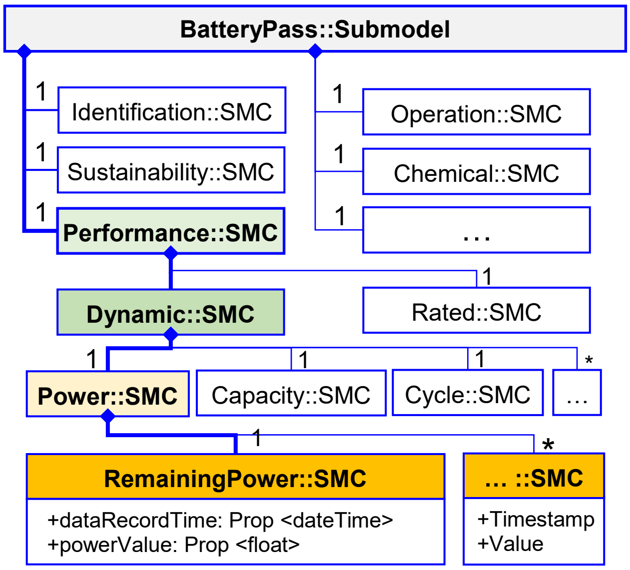


Figure 12: Reduced UML-Diagram of Battery Passport, based on [11], highlighting the data recording element

An example of this is shown in Figure 13, where the left-hand side shows the real-time data from the UAV in the DPP for the remaining power and its corresponding time stamp. The results over time are shown on the right, where a decrease can be discovered in the time-ordered data set. As with all DPP data, this data is available not only to the internal system for processing in terms of autonomous decision making and event notification, but also to external authorized requesters such as robotic maintenance systems, PLM software or whoever needs the data.

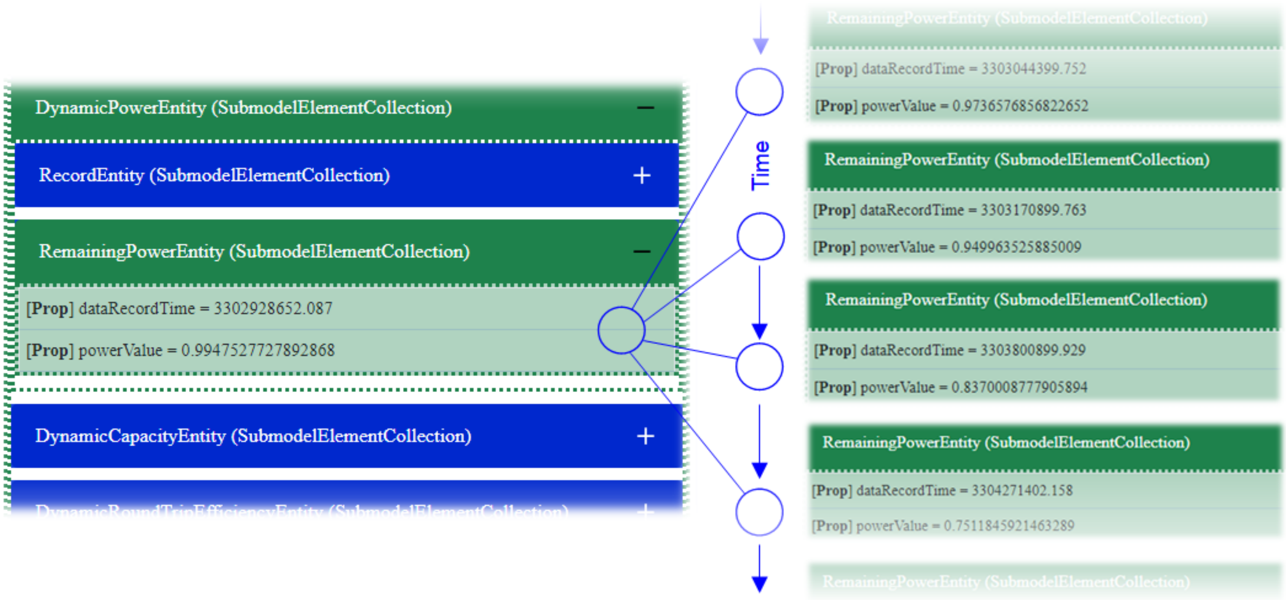


Figure 13: Real-Time Data mapped into the DPP by AAS server, e.g. the remaining power of battery

4.2. DPP in the IoT scenario

The use of the DPP is illustrated by a simple interaction between two actors in our Maintenance Simulation Model (**MaSiMO**), an experimental MRO-CPSS-IIoT environment that is part of our **Industry 4.0 Plateau**. In this scenario, the UAV acts as a service requester, while a robot acts as a service provider. Here, the proactive AAS continuously monitors selected system health indicators, processes them with built-in algorithms and makes decisions based on set values and thresholds. When these thresholds are reached or predicted to be reached, the UAV's AAS determines the appropriate action, such as initiating MRO treatment requests to the robot.

This process is realized by an *EventManager* state machine that supervises preconditions specified by either the DPP or manual configurations. Figure 14 illustrates the WebUI for manual event configuration, where users can select observable indicators, define their thresholds, and specify recovery values for forced recovery scenarios. These configurations are directly linked to one or more event codes, with each code corresponding to a specific service task – such as an inspection request – or a combination of service tasks sourced from a Bill of Processes (BoP), as depicted in Figure 15. Tasks can range from general maintenance slots to detailed requests, where the AAS specifies the necessary MRO “capabilities” for the asset, such as inspection, repair or replacement. In turn, the MRO service provider evaluates its ability to meet these requested capabilities with the available “skills.” Here, "capability" means the overall functional requirement, while "skill" refers to the specific methods implemented to fulfill that requirement, which may vary in approach and quality based on the resources available (e.g., automated, manual, or specialized equipment).

To utilize this, the *EventManager* implements a multi-criteria decision-making algorithm that continuously monitors and analyzes the asset properties, including battery performance, engine efficiency, and environmental conditions. The logic of the algorithm in the *MultiCriteriaDecision-Making* state evaluates whether any thresholds have been crossed. When such thresholds are detected, it determines which event codes and their associated tasks need to be requested. Under normal operating conditions, the transition logic directs service requests to the subsequent state, *SendOrderServiceRequester*, for dispatching requests to IoT participants – initially broadcasting a message to all stakeholders via a registry service and later facilitating bilateral communication on demand. Conversely, if any abnormalities are detected, the system transitions to an Error state, where issues are recorded for further analysis.

Figure 14: Configuration of the event triggers with rated and dynamic values (limit + real time) from the DPP in relation to the selected entity (here the battery)

In addition to evaluating the management of the DPP, we investigated how the DPP in the proactive AAS supports the internal processing of events by retrieving rated data from it. Furthermore, the exchange of the DPP or parts of it has been proven in accordance to I4.0 conform interactions. The UAV battery introduced in Chapter 4.1 is used, with real-time data monitored against the rated limits that the AAS retrieves from the DPP. In this way, the DPP enhances the decision-making process within event management. We have defined a scenario where the battery passes three thresholds during discharge, each threshold being associated with pre-defined events such as explained before. The event manager initiates a “Call for Proposal” that includes all required tasks, represented as capabilities, sent via a registry server to all IoT participants. For overview reasons, the call here is only responded to by the inspection robot AAS. In order to execute the task, the robot needs the basic geometry data from the UAV, as it is in the DPP. Thus, the robot requests the UAV to send the related part of the DPP, including length, width and height of the UAV, identified via an ECLASS semantic ID.

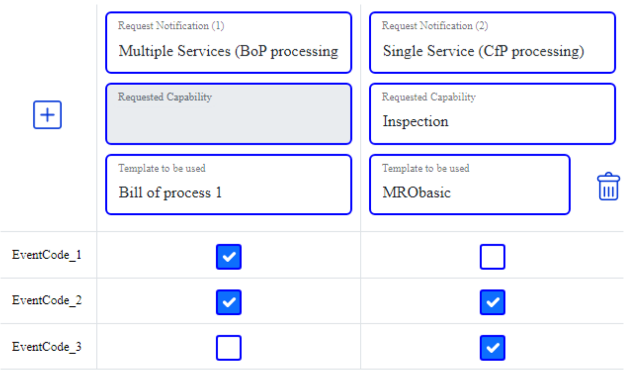


Figure 15: Configuration of tasks depending on events that have occurred

In fact, the document processing is realized by another implementation of capabilities and skills, the explanation of which is not part of this paper. After the UAV has checked the access authorization (no sophisticated control is implemented yet), it returns the desired DPP data and the robot continues its process. When completed, the robot or the UAV updates the UAV's DPP with a service record, which can consist of various data, from a time-stamped service notification to full reports (Figure 16). This DPP data is used to improve upcoming events or as requested input for other participants in the IoT organized along the value chain.

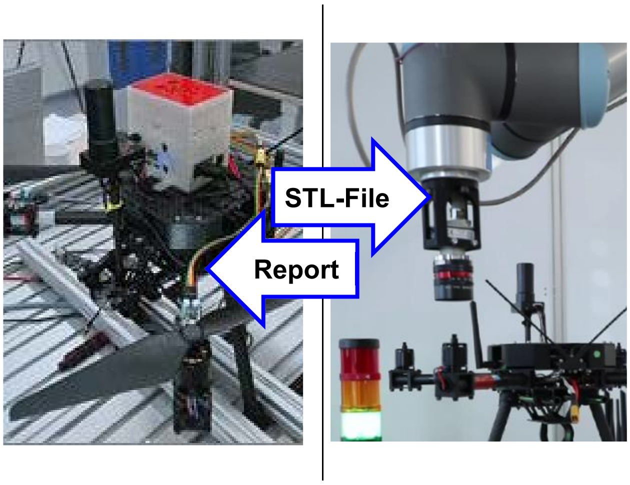


Figure 16: MRO SP (right) inspects MRO SR (left); *DPP data is exchanged during the operation.* *These include the geometry as input to the SP and, in return, data on the service executed as a record set for the SR's DPP.*

In summary, the integration of the DPP in the proactive AAS allows a low-barrier and flexible-content creation. It was successfully applied to an aircraft surrogate. Regardless of the fact that the DPP will sooner or later be made mandatory by EU legislation, it supports internal process flows of the proactive AAS. Finally, the exchange of information, based on the DPP and in I4.0 conform schema, between different IoT participants has successfully been demonstrated.

5. CONCLUSION AND OUTLOOK

The development of the Digital Product Passport (DPP) is being fostered by the European Union with the aim of tracing products from 2027. The motivation is to improve sustainable production, which requires transparent, comprehensive and lifecycle-wide product data along the value chain. Although the first official implementations are focused on selected sectors such as batteries, textiles or electronics, the scope is expected to broaden. In general, the use of the DPP concept promises significant benefits in managing traceability, integrity and interoperability of data, which is critical in sectors such as aviation – in particular in the MRO sector, where the trace of part's life data, including part exchanges, is crucial.

As we have shown in previous papers, the Asset Administration Shell (AAS) with its standardized metamodel, provides a comprehensive digital solution for assets' data organization, flexibility and interoperability across complex systems such as an MRO CPSS. Thus, the present paper elaborates the question how the AAS can enable a low-barrier, content-flexible implementation of the DPP. By integrating the DPP into a proactive AAS framework, we demonstrated its successful application to an aircraft surrogate, facilitating seamless information exchange between IoT participants in compliance with Industry 4.0 standards. This approach not only aligns with upcoming EU regulations but also supports internal processes of the proactive AAS by providing a standardized, dynamic method for managing product lifecycle data. The study began by deriving the essential content requirements for a DPP, including static elements such as the nameplate, bill of materials (BoM), technical specifications, and dynamic components like real-time performance metrics and sustainability indicators.

While the conceptual integration of technical data was effective, challenges remain, particularly with the inclusion of sustainability metrics like carbon footprint and material sourcing. Additionally, managing data provenance and authenticity across distributed supply chains needs further refinement. The implementation revealed several key challenges:

- **Data** Integrity: Ensuring the accuracy and consistency of data across different systems and throughout the asset lifecycle to prevent errors and maintain reliable information.
- **Access** Control: Developing secure, role-based access mechanisms to protect sensitive data and ensure that only authorized users can view or modify specific information within the DPP.
- **Content** Customization: Adapting the DPP to accommodate various asset types and industry-specific requirements, particularly in the MRO and aviation sectors, where data needs can be highly specialized.
- **Document** Management: Enhancing the AAS with capabilities to autonomously manage and exchange documents, such as individual DPP components, across different systems and stakeholders.
- **Interoperability**: Improving the AAS's integration with diverse IoT platforms to ensure seamless and consistent data exchange across a broad range of industrial systems.

Future research should address these challenges by refining the AAS-DPP framework, focusing on enhancing data integrity, improving access control, and optimizing document management. Furthermore, expanding the ecosystem of reusable submodels through collaborative initiatives like

Manufacturing-X will support the development of a more robust, interoperable, and transparent data-sharing infrastructure. These advancements are crucial for scaling the AAS-DPP framework across industries and achieving effective asset management and maintenance.

6. ACKNOWLEDGEMENT

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7. ABBREVIATIONS

AAS	Asset Administration Shell
BP	Battery Pass
CE	Circular Economy
CfP	Call for Proposal
CPS	Cyber-Physical System
CPSS	Cyber-Physical-Social System
CX	Catena-X | Catena-X Automotive Network e.V
DPP	Digital Product Passport
EASA	European Union Aviation Safety Agency
I4.0C	Industry 4.0 Component
IDTA	Industrial Digital Twin Association e.V.
IIoT	Industrial Internet of Things
IoT	Internet of Things
IT	Information Technology
MaSiMO	Maintenance Simulation Model at DLR-MO
MRO	Maintenance, Repair and Overhaul
OPC UA	Open Platform Communication UA
PI4.0	Plattform Industry 4.0
Prop	Property
Ref	Reference
SM	Submodel
SMC	SubmodelElementCollection
SML	SubmodelElementList
SP	Service Provider
SR	Service Requester
WebUI	Web-based User Interface

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