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An Auditable PPR Framework for the Digital Product Passport using AAS-based Process Passports

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Abstract

Starting with 2027, the first product groups in the EU are legally bound to introduce the Digital Product Passport (DPP) as an enabler for circular economy by sharing product-related information along the entire life cycle. While the DPP also provides new business opportunities through data transparency, companies face uncertainties regarding design, setup, operation and maintenance of the required IT infrastructure, and securing their business secrets. In this paper, a framework for the DPP is presented, enabling detailed traceability of individual processes, and recalculation, verification and extension of DPP key performance indicators (KPIs) in case of audits or changing DPP requirements. Through referencing between products and processes within the Asset Administration Shell (AAS), a verifiable DPP is envisioned, facilitating services like accountability for green audits and aggregation for a comprehensive Life Cycle Assessment (LCA). Finally, the framework is applied in a case study within tool manufacturing for the calculation of the Product Carbon Footprint (PCF).

Keywords: Digital Product Passport, Asset Administration Shell, Product Carbon Footprint, Data Space, Ecosystem

1 Introduction

Manufacturing Industry is challenged by the Green Deal to enable circular economy by sharing product-related information through the Digital Product Passport (DPP) along the entire value chain [1]. While the DPP enables new business opportunities, sharing data within competitive markets, such as in the manufacturing industry, is often risky. This leads to uncertainty among companies, and a struggle on setting the right course between data transparency in the value chain and securing their own digital sovereignty, without providing too detailed insights into core competencies and business secrets. Initiatives like Catena-X and International Manufacturing-X are set on enabling collaboration in value creation networks using data space and data and service ecosystem technology, and must therefore address a common trust plane, e.g. Gaia-X, for transparency and sovereignty of data in the value chain. To enable the DPP, Pellegrini et al. [2] identified four major fields of challenges: (1) Product ID, (2) Product Data Carrier, (3) Digital Connector, and (4) IT Architecture, with the latter two requiring companies to operate an IT system capable of identifying, locating, storing, sharing and managing interoperable data and data access along the product life cycle. This further introduces the challenge of collecting, preparing and computing data into required information and key performance indicators, and the requirement of employing trained IT personnel or paying external services to setup, operate, and maintain such an infrastructure. For companies, the environment remains uncertain, due to lacking mature and out-of-the-box technologies for sovereign collaboration in data spaces and ecosystems, as well as software modules for dynamically building DPPs from aggregated manufacturing data. Schaltegger and Burritt [3] mention, that there exist limited methods for systematically organizing the collection and sharing of environmental data within

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companies. Furthermore, the built DPP is required to enable detailed traceability along the value chain, and possible verification or investigation of non-conformance of product or even process data by auditors. Therefore, the objective of this work is to develop an auditable and scalable DPP framework that ensures data sovereignty and introduces the Digital Process Passport (DPssP) to provide detailed insights. The framework is applied in a case study for the modelling of products and processes involved in the manufacturing life cycle stage of an injection moulded product, including the calculation of the Product Carbon Footprint (PCF) of injection mould manufacturing as a crucial early step in the value chain of injection moulded products. During the injection moulding process, the injection mould precisely shapes the injected plastic, ensuring the final product conforms to specifications and tolerances.

2 Literature review

The DPP serves as key enabler on the path to a circular economy by facilitating the collection, storage, and retrieval of relevant information throughout a product's entire life cycle. The DPP will be mandatory for products sold in the EU, with the first the product groups (e.g., batteries) starting in 2027, and is incorporated in the Ecodesign for Sustainable Products Regulation (ESPR) [1], which came into effect in July 2024.

The Asset Administration Shell (AAS) is a fundamental concept driving digital transformation across industrial organizations, also identified by Pellegrini et al. [2] to be a core contributor to advancing the DPP. By using the AAS framework a standardized digital representation for an asset can be obtained. An asset is defined as a physical or logical object that is owned or under the custody of an organization and provides either a perceived or an actual value to the organization [4]. An AAS is composed of a header and a body. The header includes details about the AAS and the asset it represents, while the body contains one or more submodels. Garrels et al. [5] mention, that these submodels can be used to implement different sections of the DPP, while AAS submodel elements are used to implement the individual data elements within each DPP section. Neligan et al. [6] design the DPP comprising of three submodels for identification, description and characteristics and environmentally relevant information with the latter including data on the carbon footprint. The primary objective of conducting a carbon footprint is to calculate a product's potential contribution to global warming, expressed as CO_2e, by quantifying all significant GHG emissions and removals throughout the product's life cycle or selected processes, in accordance with cut-off criteria [7]. A Carbon Footprint submodel template [8] provided by the Industrial Digital Twin Association (IDTA) facilitates the exchange of an asset's carbon footprint along the value chain and supports multiple PCF values using various calculation methods and assumptions. The German Electro and Digital Industry Association (ZVEI) [9] demonstrates the dynamic calculation of the PCF for a control cabinet, using the AAS to facilitate the exchange of sustainability information among business partners within a value network. As, to fully utilize the capabilities of the AAS and to effectively implement the circular economy, it's essential to consider all stages of the life cycle and involve relevant stakeholders, Pourjafarian et al. [10] emphasize a multi-stakeholder approach to both the AAS and the DPP. Plociennik et al. [11] demonstrated for the sorting of electronic waste, in the end-of-life stage, that the DPP can be expanded by allowing stakeholders at every stage of the life cycle to both access and contribute content.

While the aim of the DPP is to facilitate easier digital access to essential product-specific data concerning sustainability, circularity and regulatory compliance, the DPP is not designed as a tracking and tracing tool but can incorporate traceability data when relevant [12]. Alt et al. [13] argue, that the DPPs product-centric approach limits its applicability, and in addition to the DPP, address a concept for a DPssP, which provides more detailed traceability of the individual processes. The concept of a DPssP builds upon the idea of a DPP but focuses on documenting and tracking the processes involved in creating, manufacturing, distributing and disposing of a product. In comparison to the DPP, DPssP is oriented more towards internal company processes and is geared towards enhancing process optimization and driving continuous improvement initiatives rather than catering primarily to consumer needs. A holistic DPP requires data and information from every step of the product's production process [14]. The DPssP is expected to determine energy consumption and CO_2 emissions on a process-specific level. Given its close connection with the DPP, their integration across the entire product supply chain is both feasible and advantageous.

3 Design of an auditable DPP Framework using DPssP

This work presents an auditable framework for the DPP, enabling detailed traceability of individual processes to enable comprehensive verification of process data, and thereby providing concepts for designing future-proof IT architectures for the DPP. As auditing is not only product-, but also process-related, it involves not only the product and its materials, but also the context of production, like machinery and environmental conditions. Therefore, the use of DPssP plays a key role in this framework, by combining a Product-Process-Resource (PPR) approach with the DPP and the AAS. Figure 1 shows the relationship graph between Digital Product and Process Passports, with resource being a specialization of product, e.g. a machine or manufacturing utility, that may be used in a manufacturing process to produce a product without being completely consumed by or installed in the resulting product.

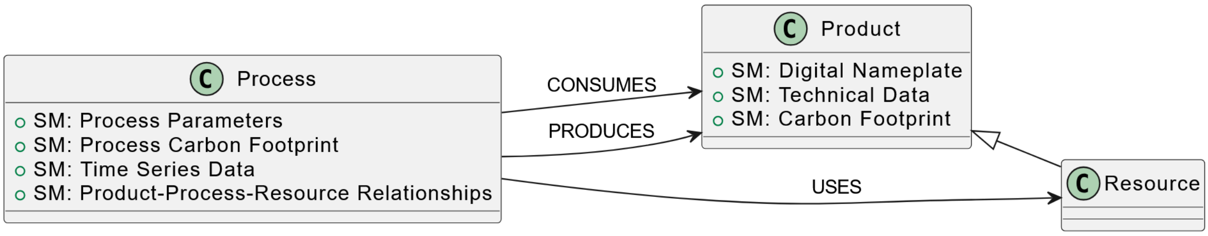

Figure 1: Diagram of the high-level Product-Process-Resource (PPR) model, including the relevant submodels for the AAS of the Digital Product and Process Passports, and their relationships.

The DPP is also similarly applied for resources as for products with the following submodels used: Digital Nameplate [15], Technical Data [16] and Carbon Footprint [8]. Other submodels may also be present depending on the application. The DPssP is dependent on the type of process and the relevant data associated. Next to the Time Series Data [17] submodel, the Process Carbon Footprint contains process key performance indicators (KPI) relevant for the calculation of the PCF of the respective process. These may be aggregations of collected timeseries data like electrical energy consumption as integration of measured electrical power values. The key of the DPssP is the Product-Process-Resource Relationships submodel, that is describing the relevant one-to-many relationships between the process and the respective products and resources using the Hierarchical Structures enabling Bills of Material submodel [18] provided by the IDTA. This is following a top-down approach, describing the relationship to other assets by referencing the global asset ID. As a result, the life cycle of products, including their manufacturing processes, and referenced resources involved in manufacturing, can be represented as a graph using a set of AASs. This provides the basis for calculation of a PCF from the properties provided in the different life cycle phases within the PPR graph, or for calculation and aggregation into a comprehensive Life Cycle Assessment (LCA), if all relevant data is available.

To integrate and operate the above-mentioned DPP framework certain aspects in the IT architecture must be considered: **(1) a data acquisition system** is employed, especially with a focus on tracking relevant data for CO2e emissions. Industrial grade solutions may use Supervisory Control and Data Acquisition (SCADA) systems. Al Assadi et al. [19] demonstrate an automated environmental impact assessment using MQTT protocol as a basis for tracking energy usage and CO2e emissions via AAS. Ajdinović et al. [20] also show that event-sourcing can be used to capture and store process data in AASs. They further show that **(2) data aggregation capabilities** are necessary in an IT system to dynamically generate the relevant data (e.g. electrical energy from power measurements) for the DPP, or accordingly the DPssP proposed in this work. As storing and querying multiple interconnected AASs efficiently at large scale is currently problematic, a **(3) data storage and management** system is useful, either for storing or indexing data. With the overall PPR model representing a graph, graph database technology is feasible for handling the complexity of the references between the assets, while also SQL, or NoSQL databases are applicable. The system must ensure the PPR graph is easily accessible and manageable for subsequent querying and computation. While the format for backend data storage may be different from the AAS syntax, the **(4) integration of life-cycle data** is essential for ensuring that all life cycle stages can be linked. This involves providing capabilities of importing, exporting one or multiple assets with its relationships as AAS or Composite AAS, which encapsulates the graph. They must dynamically generate AASs from the storage system to conform to Type 1 or Type 2 AAS. Additionally, **(5) querying and computation** of e.g. the PCF in the PPR graph must be efficient and simple to use. Further, **(6) data security and access control** are crucial when interacting with other external participants, as process data contains sensitive information. Ecosystems, data spaces and their connectors as well as Composite AAS must ensure data sovereignty by implementing strong access mechanisms, including authentication and authorization based on a combination of attributes, roles, and policies. Whereby an attribute may be any element of an AAS submodel or a context depended input like a verifiable credential and the policies may be internal or context depended and relying on any combination of the attributes. The access control can be extended with technologies like Compute-to-Data, Selective Disclosure, and Zero-Knowledge Proofs (ZKP) to protect data while enabling secure computation. Finally, **(7) auditability** must be supported. This allows verification of process data, e.g. timeseries, or files, such as images. Here, too, a distinction between extern and internal company boundaries must be made. Externally Blockchain anchoring technology for traceability, possibly combined with file pinning for transparency, or ZKP for long living independent verification possibilities may be employed where trust is an issue, providing transparent and verifiable records of data and transactions. Internally the processes of import, export, aggregation and transformation of data related to DPssP must be auditable.

4 Case study

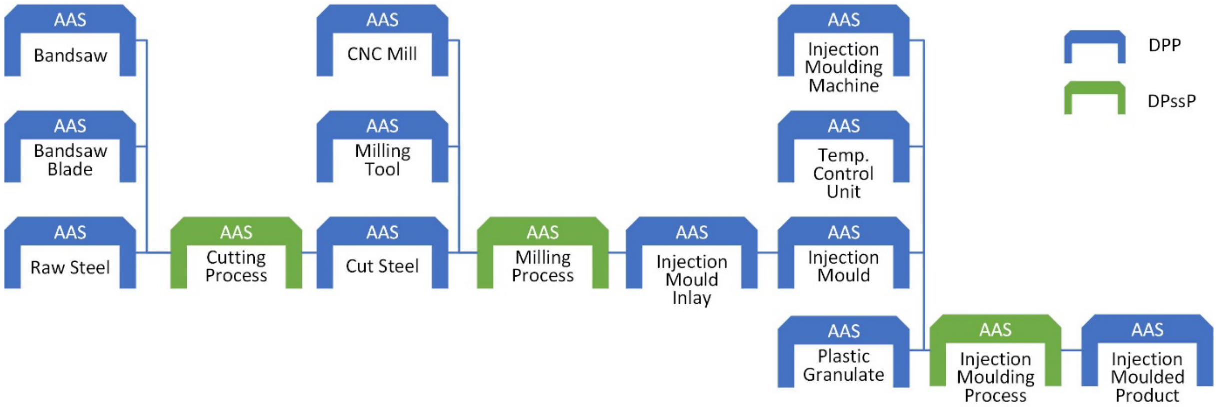

Figure 2: AAS-based Digital Product and Process Passports in a cradle-to-gate life cycle in injection moulding

The case study presented in Figure 2 outlines the value chain from tool steel to the final injection moulded product, with a focus on a single inlay of an injection moulding tool. A component is cut from tool steel using a band sawing machine and then machined in a CNC milling machine. The inlay is installed in an existing injection mould, and the injection moulding process is carried out. All the products, processes, and resources detailed in the use case are represented as either physical or logical assets using the AAS.

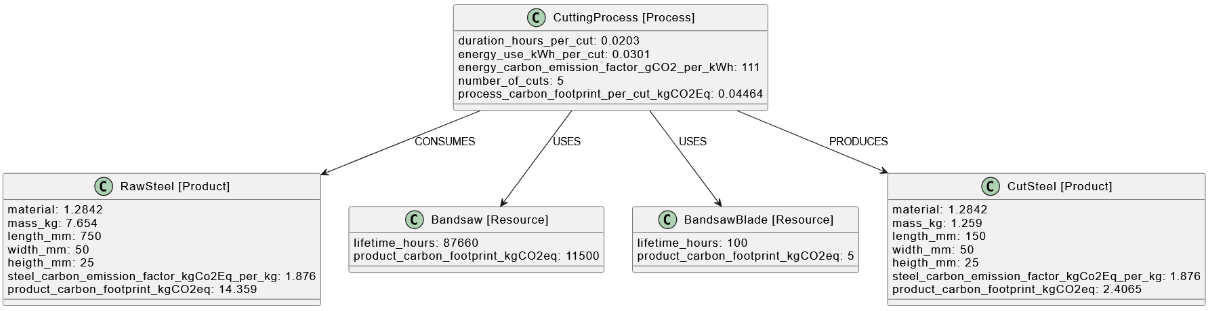

Figure 3: Digital Product and Process Passports (simplified for usability and readability) with relevant data for PCF calculation for the first Process Passport (CuttingProcess) within the life cycle presented in Figure 2.

The first part of this life cycle regarding an automated band sawing process is shown in detail in Figure 3. The process data shown is resulting as KPIs for duration per cut, energy per cut and number of cuts (Process Parameters submodel) from timeseries data collected from a power meter during the process (Time Series Data submodel) and calculated for the PCF per cut (Process Carbon Footprint submodel).

As a designated query language for the AAS does not exist yet, for the calculation of the total PCF for a product the relevant properties must either be extracted individually, or the AAS syntax translated into Resource Description Framework (RDF), to use SPARQL for graph queries. Nevertheless, this is currently not a straightforward task, as SPARQL queries within the AAS can quickly become complex, when having to query relationships between multiple assets through the PPR Relationship submodel, e.g. in a composite AAS, that is including the whole graph.

Currently having a combined approach of recursively extracting properties and importing into a flat and easy to query property graph seems reasonable for the application of PCF calculation, while e.g. making use of the modelled semantics would make a sophisticated approach. For comparison, ZVEI [9] use a variable called “Footprint Information Combination” to already aggregate the PCF values for subcomponents of a control cabinet, to enhance usability. Therefore, in this case study, the submodel properties are recursively extracted into a flattened property graph, and imported into a neo4j graph database, omitting unnecessary data points for readability. The database could then be used to calculate the Process Carbon Footprint and the Product Carbon Footprint in a single graph query.

5 Conclusion

This work presented a first step into an auditable DPP framework, by extending the DPP with the DPssP and discussing a suitable IT architecture. Auditing is becoming especially more relevant in the future with the environmental, social, and governance (ESG) framework receiving more attention. The Digital Process Passport offers great potential by providing detailed information, making it useful for proving compliance within ecosystems. Additionally, exploring the use of ZKP in combination with the DPP could strengthen the framework. Future work should focus on improving the IT architecture around the framework regarding its application in ecosystems, using Compute-to-data, Selective Disclosure and ZKP, and enabling automated auditing.

6 Acknowledgements

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