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An Asset Administration Shell-Based Digital Product Passport as a Gaia-X Service

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Abstract

Within the context of the Sustainable Product Initiative of the EU, product passports will likely be required in more and more sectors. However, their introduction is associated with challenges considering data collection and technical implementation, as the degree of standardization and availability of technical implementations for product passports is still low. To address these challenges, this work presents a digital product passport using asset administration shells to enable standardized connectivity via REST interfaces and, thus, standardized information exchange. The data model created contains submodels that specify information concerning the entire lifecycle of the product. Furthermore, these data enable the determination of the carbon footprint of the products as well as remanufacturing. The product passport will be implemented as a Gaia-X service to enable a secure and decentralized collection, exchange, and storage of product related data. The developed digital product passport and the Gaia-X ecosystem will be set up as demonstrators in the Learning Factory Global Production.

Keywords: digital product passport; asset administration shell; Gaia-X; carbon footprint; circular economy

1. Introduction

The aggravating climate crisis, stricter legislative requirements, and increasing market pressures force manufacturing companies to improve their sustainability significantly [1]. Therefore, laws and regulations provide saving targets by specifying, e.g., the carbon emissions caused and the energy consumed by companies [2]. In order to guarantee an accurate measurement of such environmental impacts, using a digital product passport (DPP) will be mandatory in the future, e.g., in battery production [3].

However, realizing DPP entails various problems. Although DPPs are considered an essential component for increasing the transparency of the ecological footprint of companies, only application-specific isolated solutions exist to date. Hence, there is no uniform technical standard for DPPs in practice or science [4]. Standardized, accessible, and interoperable solutions can help to make DPPs applicable for as many potential users as possible. Especially for small and medium-sized enterprises (SMEs) in the manufacturing industry, the technical integration and usage of the DPP needs to be as simple as possible [5,6].

Furthermore, complex value chains pose a hurdle for the transparency and traceability along the life cycle of products to reduce emissions and an efficient circular economy since missing transparency of product life cycle data increases the difficulty of taking back products and optimizing their circular recovery, e.g., by recycling or remanufacturing [7]. However, a circular economy can save considerable amounts of carbon emissions and energy [2,8]. In particular, remanufacturing offers high savings potentials since it enables the value retention of products on an industrial scale compared to other circular strategies [9]. However, detailed data, e.g. original product manufacturer or product type, is often missing for

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efficient remanufacturing, creating uncertainties. The availability and exchange of information on returning products is crucial for the management and control of end-of-life parts, reverse logistics, and hence a successful implementation of a circular economy [10–12]. DPPs are seen as a fundamental enabler to overcome these uncertainties by providing a seamless exchange of information between different network partners in a supply chain [13].

Therefore, this paper presents a DPP using asset administration shells (AAS), i.e. a standardized digital representation of an asset [14], to enable standardized, decentralized information exchange using REST interfaces. Apart from this, the corresponding data model of the developed DPP enables accurate event-based tracking and specification of relevant product information along the whole product lifecycle. On the one hand, this may increase the transparency of products regarding sustainability criteria such as the origin of materials and components following legislative requirements (e.g. Corporate Sustainability Due Diligence Directive CSDDD), emissions in the value chain, or usage data. On the other hand, detailed information regarding the input materials, the manufacturing process, and the end product itself facilitates circular activities and especially remanufacturing [15]. To further guarantee a secure and decentralized exchange and storage of data, the developed DPP is implemented as a service offering within the European data infrastructure project Gaia-X. In contrast to existing proprietary platforms, the data in Gaia-X is stored decentralized at the respective companies and exchanged via common standards and centralized, standardized services, so-called federation services. Furthermore, the sovereignty and security of the data comply with European standards [16–18].

The remainder of the present paper is structured as follows: Chapter 2 discusses the state of the art regarding product passports and comparable approaches and initiatives, as well as the calculation of the carbon footprint and the realization of a circular economy in this context. Based on these insights, Chapter 3 presents the developed DPP. It is subdivided into the definition of requirements regarding the data and the data structure of the DPP (Chapter 3.1), the implementation with AAS (Chapter 3.2), and the description of the realization as a Gaia-X service along the value chain (Chapter 3.3). Chapter 4 specifies an exemplary application and realization of the DPP in the Learning Factory Global Production at wbk [19]. Chapter 5 concludes with a critical discussion of the presented concept and an outlook on future research activities regarding the developed DPP.

2. State of the Art

Although industrial production is one of the largest carbon emitters from a global perspective, it is still far from climate neutrality [4]. Therefore, systematically reducing and optimizing carbon emissions and energy consumption in production, or production networks and supply chains, has gained increasing attention in research [20,21]. In this context, initiatives such as 'Catena-X' in the automotive industry, 'Together for Sustainability' [22] in the chemical industry, or the 'Estainium Association' [23] and the commercial software 'SiGreen' based on Estainium [24] focus primarily on standardizing the calculation of carbon emission data as well as the infrastructure and communication format of this data [25]. However, these approaches exclusively deal with the calculation of emissions data without deriving further information from it, e.g. for end-of-life strategies.

Apart from the pure collection and calculation of carbon emission data, companies need to rethink their existing value creation patterns to achieve their overarching goal of more sustainable production. The CE represents a broad field of research that may contribute significantly to ecologically sound production practices [26,27]. However, information on product conditions and specifics is often only transferred according to predefined sorting classes [28]. The traceability of individual manufacturing products does hardly exist [29]. Identification of exact product specifications is usually based on the product number, whereby precise information on, e.g., type is missing [30]. Accordingly, there is a lack of holistic approaches that provide relevant product information at the end of the product life cycle by increasing transparency throughout the entire product life cycle.

By being capable of resolving the aforementioned issues regarding data availability and collection and enabling increased circularity in global production networks, DPPs have recently gained increasing attention in research and industries. According to the Wuppertal Institute, a DPP comprises product data from all its life cycle stages and thus specifies materials, components, and information regarding circular activities such as repairability, replacement of spare parts, or disposal [5]. Associations and initiatives, such as ZVEI, use product passports to compile carbon emission data over the life cycle. In particular, the concept of AAS is used by this approach to simplify the exchange of information [31]. However, the approach solely focuses on the pure collection of carbon data neglecting the opportunities of DPPs for enhancing the CE. Similarly, Catena-X aims to provide standardized, global data exchange and strongly focuses on data sovereignty. However, the corresponding DPP is limited to automotive value chains and does not consider circular aspects [32]. Focusing on facilitating the CE, for example, [33] developed an AAS-based DPP for the entire product life cycle to simplify sorting and recycling electronic devices through the information the DPP contains and using machine learning. Nevertheless, carbon emissions, in particular, as well as the connection to a standardized exchange system, are neglected.

Also, the potential of DPPs has already been recognized, especially in the context of remanufacturing. For example, [13] use a simulation model to improve the remanufacturing process efficiency by using product life cycle information. DPPs allow the seamless writing and transfer of respective lifecycle information, improving their traceability [30] and reliability. Based on this information, well-founded decisions concerning circular activities such as remanufacturing can be made [34].

However, existing approaches in the context of a DPP-enabled CE are often sector-specific and differ in terms of the actors involved and their roles, e.g., governmental organizations and their functions. Although most DPPs have functions to support the CE, they are limited to specific use cases, for example, the transparency about the materials used, to enable more efficient dismantling [5,35]. So far, no holistic approach integrating DPPs with data exchange policies like Gaia-X exists for entire value streams, focusing on circularity and remanufacturing.

Therefore, the present paper aims to solve these issues by providing a DPP whose generic data model is applicable to different industries and all corresponding network partners along the life cycle of a product. Due to the standardized data format (AAS) and transfer (Gaia-X), information can be exchanged seamlessly between network partners, overcoming the problem of product-specific data availability.

3. Methodology

In the following, the methodology to develop an AAS-based DPP as Gaia-X service is presented. The used methodology is subdivided into three steps. At first, the requirements for the data structure, e.g. contained information, are defined (chapter 3.1). Secondly, the AAS architecture for the DPP is developed (chapter 3.2). As a last step, the integration of the AAS-based DPP into the Gaia-X ecosystem is presented (chapter 3.3).

3.1. Requirements for the Data Structure

The following subchapter defines several requirements regarding a suitable data structure for implementing a DPP from an application perspective to address the outlined research deficits. In addition, the DPP to be developed should be easy to use in industry and comply with legal requirements or information obligations. The DPP should also be used in the context of the CE.

Therefore, the DPP should contain information from all life-cycle phases, that can also facilitate the identification of old products, disassembly, and remanufacturing, as well as repairs and recycling.

Furthermore, the DPP should contain information about the product's carbon footprint, or it should be possible to calculate this based on the information it contains.

The data structure of the DPP should, therefore, contain the following information on different areas of the product and its life cycle, as also depicted in Figure 1:

- **General Data:** General product data, e.g., for identification, such as product type, serial number, warranty, year of manufacturing, and any information on energy consumption and efficiency, should be included here. Furthermore, existing standards and certificates can be included. In addition to informing the customer, this section can also be used to fulfill legal requirements regarding documentation.
- **Bill of Materials:** The used materials should also be listed, especially if some are toxic or must be disposed separately. Further information can include the quantities of materials used and the materials per part and component for simplifying recycling. In addition to information for recycling, information on the origin of materials and the carbon footprint of materials may also be included.
- **Manufacturing & Transport:** Information on the manufacturing process and transport is also required, particularly for determining the carbon footprint. The locations of various production steps, the processes and means of transport used, and the energy consumption are relevant here. However, an aggregated value for the carbon emissions may be stored principally to avoid disclosing too many internal details (cf. chapter 3.3).
- **Design:** Furthermore, the DPP should provide repair and disassembly instructions. These can be aimed either directly at the end-user or specifically at workshops and remanufacturers and thus contain additional information on complete modules and components. In addition, information about security and repair-critical parts or parts prone to failure and wear can be added.
- **Life-cycle:** To facilitate a CE, the DPP should also contain information on product use, maintenance, and repairs. This makes it easier to assess the product's condition or the individual components and modules in the event of repairs or at the end of the life cycle and can facilitate a decision toward remanufacturing or recycling.
- **Carbon Footprint:** The carbon footprint of all used materials, manufacturing processes and transports is collected and aggregated to provide information to end users and facilitate eco-friendly decisions. Furthermore, the impact of remanufacturing on the products' carbon footprint can be presented transparently.

Overall, the data structure of the DPP should offer the possibility to map the information mentioned above. However, since some of this information is worth protecting or unavailable, the DPP should also work with less information or lower information granularity. This may be necessary, especially during the introduction of the DPP, while ensuring later extensibility to expand the DPP and its functionality.

To access the information contained in the DPP, extensible and compatible interfaces are required to enable broad applicability in different industries. This must be considered when modeling the data structure (cf. chapter 3.2).

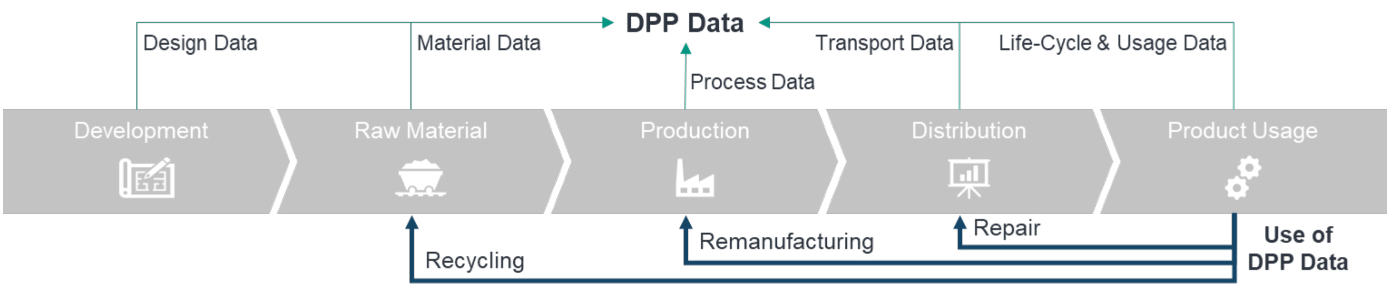

Figure 1: Data collection for DPP along product life-cycle

3.2. Asset Administration Shell-Based Architecture for a Digital Product Passport

AAS serves well as a technological enabler for a DPP for multiple reasons. Firstly, the AAS defines standardized terms to model assets with its metamodel [15] and allows for excellent modelling flexibility due to the modularity of its metamodel. Secondly, the AAS allows for interoperable information integration due to available reference implementations of communication technologies such as 'OPC UA' or 'MQTT' [36] and interoperable information access by a defined REST-API of the AAS metamodel that is standardized with an 'OpenAPI' specification. Since REST is the most widely used standard in web communication, usage of the information in an AAS by other web services can be realized easily. Lastly, the AAS allows for decentralized information storage and controlled information access, making it suitable for usage in a service-oriented architecture that is manageable even in large systems by providing the principles of modularity and separation of concerns. For example, different entities that are responsible for the integration, storage, and usage of data of DPP based on AAS can be deployed on different servers with different access rights and functionalities. This is especially important since different parties, such as manufacturers, retailers, users, and remanufacturers, will consume data from and provide data for a DPP. Since the DPP data is aggregated and formatted as JSON files and many contained information are required also by law, the additionally required capacity for data storage is relatively low.

Thus, AAS serves as a suitable technological basis for realizing a DPP that provides modularity and flexibility concerning data modeling and access over the life cycle of a product. When realizing a DPP with an AAS, it is vital that not only static information, i.e., type-based information of a product such as design data or manuals, can be considered but also dynamic information, i.e., instance-based information of a product such as production-related data. Especially during production and logistics, incorporating data in the DPP should be fully automated for each state transition of the product by utilizing microservices with simple interfaces responsible for these tasks. Additionally, there should be services that use the information stored in the DPP and aggregate it into new information. For instance, a service could exist for calculating the product carbon footprint based on the product design, production, and logistics data. With this modular and service-oriented architecture of DPPs, data and functionalities are more easily manageable. Moreover, future extensions in data or functionality can be considered by extension with new services without changing the running system.

3.3. Integration and Data Exchange via Gaia-X

Inter-company data exchange becomes necessary since multiple parties or companies are part of a value chain. Unfortunately, when sharing data about the product and its production processes, the data security and sovereignty of critical information is critical to increase trust in the value chain. The DPP is realized as a Gaia-X service to ensure these aspects and, therefore, facilitate the usage of the developed DPP. Apart from fulfilling requirements regarding security and sovereignty, this also enables an easy distribution and application of the DPP, especially for SMEs, since no proprietary platform is needed.

So, all required data is stored decentralized by the data owners themselves (see Chapter 3.1). Each of these servers is registered in Gaia-X. Therefore, the identity and security of each server and company are assured since a formal Gaia-X registration process needs to be carried out for the users, the service and data providers, as well as the used infrastructure, such as AAS servers [cf. 37]. Within the AAS servers, the production processes and product information is stored according to the data structure presented in Chapter 3.1. In addition, information on how many parts or materials are from suppliers, use which modes of transport, and which transportation companies is also contained in the single AAS servers to create a link to the corresponding information at the other servers. So, data exchange along the value chain of a product is designed as depicted in Figure 2.

When a DPP is needed, e.g. by a remanufacturer, the DPP Gaia-X service accesses decentralized AAS servers over their REST-API, starting with the last company in the value chain. It gathers necessary data and seeks needed data from other companies. This process continues along the value chain until the required DPP is complete. To ensure that only the required information is transferred and used for the intended use, the access and exchange are controlled and executed through the Eclipse Data Space Connector (EDC) and its REST-API [38]. Besides controlling data access and supporting the Sovereign

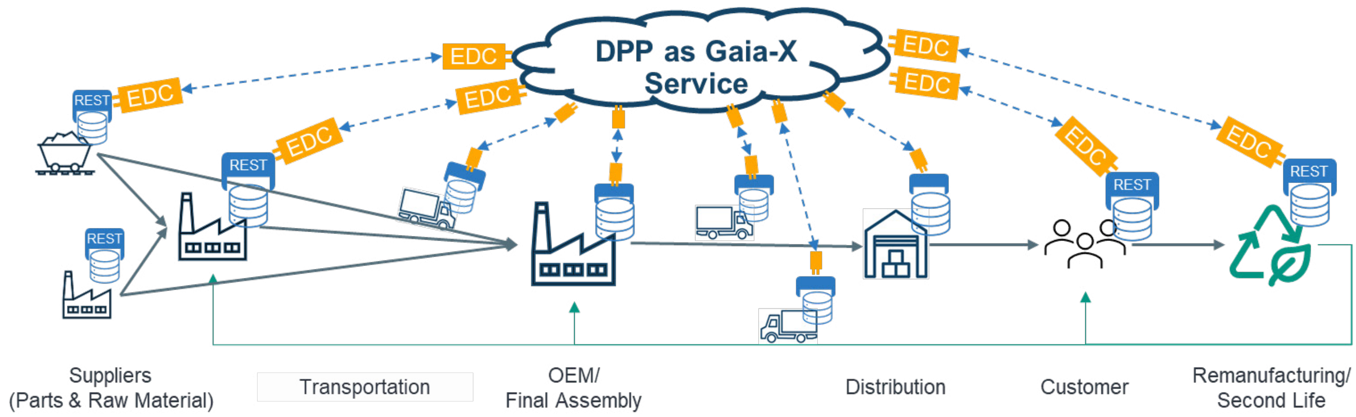

Figure 2: Data exchange along value chain from local AAS-servers to Gaia-X and the DPP and vice versa via EDC and REST

Data Exchange Federation Service in the Gaia-X ecosystem [cf. 37], the EDC handles payments for data exchange and costs generating and maintaining the DPP service.

Furthermore, to ensure the DPP does not make critical information available to unauthorized parties, different access rights refer to the Federation Services, especially the Identity & Trust Federation Service [37,39].

Therefore, six different roles are considered for the DPP and the corresponding value chain (see Figure 2). So, the suppliers only push information into their AAS servers and can only access the information of their products. Same holds for logistics partners (Transportation & Distribution) that only add information about mode and duration of transport and the corresponding CO_2 emissions. While these two only push information to the DPP, manufacturers can also access the data from them and add their data to the DPP. After the production process, the end customer can access the complete DPP, with basic information about the product, information required by law, e.g., energy consumption, its carbon footprint, and potential guidelines for usage and maintenance. While this information is uncritical regarding intellectual property rights, there are also views of the DPP for service partners that contain more sensitive information, such as construction and production information, product usage, and repair history. In order to enable a CE for the products, the DPP also contains a specific view for remanufacturers or recyclers. Besides the information for service partners, e.g., repair and usage history, this view contains detailed information about the construction of the product. So, the parts, modules and materials used are included, as well as detailed disassembly and inspection instructions and guidelines to evaluate the state of the product based on the product history. Since the DPP is based on AAS, this information can also be transferred easily from the product to the remanufacturers' systems and thus further facilitate product identification and reprocessing overall.

4. Use-Case and Application

To implement the DPP, the state transitions a product undergoes during its life cycle are stored in the AAS with all relevant information to describe them. Here, an exemplary realization of a DPP based on the previously described concepts (cf. chapters 3.1 and 3.2) is practically implemented and evaluated in the Learning Factory Global Production at wbk [19]. The product that is produced is an actuator, which is assembled in several distinct steps. This DPP is intended to demonstrate the flexibility and interoperability of the concept. However, the built demonstrator does not claim general applicability for every type of product and production process.

Currently, the official submodels of the IDTA are not fully completed and do not fit the use-case at hand perfectly. Therefore, five use-case specific submodels are created within the AAS that represents the information of the DPP to demonstrate the flexibility and adaptability of the approach. A change of the submodels towards the submodels of IDTA is simple, as far as they fulfill the requirements of the use-case. The five different submodels of the DPP are shown in Table 1.

The creation and update of the DPP during the production process should be as automated as possible. Therefore, an AAS server is integrated with the manufacturing execution system (MES) of the Learning Factory to exchange all state transitions. Small services thereby perform the integration. These services only require a list of inputs for the submodel data, as described in Table 1, and transform this information to be valid with the AAS server interface. With this, domain and AAS logic can be separated, only minimal changes in the MES system are required for integration, and AAS and MES are loosely coupled, ensuring flexibility for future changes. Furthermore, within the underlying project, an own Gaia-X ecosystem is created in the bwCloud, an IaaS platform of different universities from Baden-Württemberg [40]. This aims to demonstrate the Gaia-X principles of decentralization and federalism among the project partners and the learning factory. So far, as a first step in implementing the DPP as service in this ecosystem, the AAS server is hosted on the bwCloud.

A service is implemented that utilizes the data of the DPP to calculate the carbon footprint when requested, thereby ensuring the carbon footprint always represents the current state of the product. Lastly, an RFID tag is attached to the product, which stores a permanent link to its DPP. This allows future product users to easily access product information over the internet in the standardized AAS format and to add information on maintenance, repairs, and the usage life cycle of the products.

5. Discussion and Outlook

With the rising importance of CE, the need for information of life-cycle data and traceability becomes also more important. However, consistent and standardized cross-industry traceability systems are lacking and due to the inter-company exchange, the need for a safe, secure and standardized data exchange is mandatory.

Therefore, this paper develops an AAS-based DPP as Gaia-X service with a demonstrator in the Learning Factory Global Production. Through the use of AAS a standardized format for data exchange is applied and the offering as Gaia-X

Table 1. Submodel Overview

Submodel	Information type
General Data	General information describing the product type, the product's ID, the product's manual, and reference to every component used in the product. Due to the simplicity of the demonstrator, design information is also included here.
Manu-facturing	Event data that describes every state transition during the production contains the product's identifier, a start and end time stamp, the type of process, the used electrical power, and a list of IDs of assembled components.
Transport	Event data that describes every state transition due to transport contains information about the ID of the product, origin and target location of the transport, start and end time stamps, and the distance of the transport.
Bill of Materials	Contains material data, such as origin, type, product variant as well as the contained resources, e.g. copper or steel.
Life-cycle	Event data that describes all performed repairs on the product with information about the ID, the changed parts, and start and end time stamps.
Carbon Footprint	Contains the carbon footprint of the product in all three scopes.

service ensures a safe and trustworthy data exchange and collaboration across value chain. The information contained in the DPP aims to foster CE by integrating all life-cycle phases, enabling a targeted disassembly and remanufacturing.

However, when considering industry usage with data exchange and collaboration between different parties as well as the commercial offering of the DPP, an appropriate business model should be designed. Therefore, future work should focus on realizing a Gaia-X ecosystem and its applications for the DPP and potential business models in cross-company value chains. Here, a first step in implementing the Gaia-X ecosystem consists of a comprehensive description of the different roles and participants in the ecosystem as well as a set-up of the necessary federation services, such as the federated catalogue or the identity and trust service. Especially within the role definition, also open and business model-related question, such as which organization will offer the DPP and what are the costs and payments for the service, are further specified.

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