Digital Product Passport: Initial System Architecture with Knowledge Graphs and Data Spaces

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Abstract

The European Commission proposes the Digital Product Passport (DPP) as a key instrument to promote more sustainable manufacturing and support the transition to a Circular Economy. The DPP is viewed as a promising tool designed to provide essential information about a product's origin and composition. This transparency enables consumers to make more informed purchasing decisions, facilitates recycling processes, and enhances the potential for product repair. Recent research supports the use of data spaces to enable the DPP concept, furthermore the CIRPASS project advocates using semantic technologies to organize DPP data assets. In this paper, we propose an initial architecture of a DPP system using data spaces and Knowledge Graphs. In the preparation of this architecture, we relied on previous research that analyzed the system's requirements and investigated the process of creating and issuing DPPs in the wood processing industry context. We illustrate the architecture using carbon footprint tracking as an example, considering it as a baseline for product manufacturing information that is relevant across various industries.

Keywords

Digital Product Passport, Ontology, Knowledge Graph, Data Space

1. Introduction

Following [1, 2, 3, 4], current sustainability efforts converge toward preparing several instruments to achieve climate goals, including the Digital Product Passport (DPP). The DPP is envisioned as an instrument to propagate information about manufactured products among participants of value chains: Economic Operators (EOs) who put the final product on the market, their suppliers and the customers of the EOs. The DPP should include "information on the origin, composition, and repair and disassembly possibilities of a product, including how various components can be recycled or disposed of at end-of-life" [5], thus facilitating Circular Economy.

Several papers [6, 7, 8] already advocate the usage of data spaces for sharing DPP information among participants of value chains in a distributed and secure manner. Additionally, while current DPP-related legislation does not suggest a specific data structure for organizing DPP data asset, the results of the CIRPASS [9] research project support Knowledge Graphs (KGs) for representing DPP data assets.

In this paper, we present the initial version of an architecture of a DPP system using data spaces and KGs. This architecture is based on previous work on the requirements analysis [10] and on the examination of a process of creating and issuing DPPs [11] for the wood processing industry. Reasoning for such limitation of a scope was drawn from the prioritization of product groups by the EU Comission. Examples of the prioritized groups are furniture, textiles and footwear, detergents, etc. Prioritized product-specific DPPs will be defined by dedicated delegated acts before all other product groups. Additionally, due to the lack of precise requirements for group-specific DPPs, we are using carbon

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emissions tracking as an example to illustrate our DPP system. Refering to the global climate agenda, we assume that product carbon footprint will be a key element of DPPs across all product groups. Carbon footprint impacts in a direct or indirect way a number of the SDGs (Sustainable Development Goals) established by the UN [12], namely SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 15 (Life on Land), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities). The use of KGs, however, ensures adaptability and interoperability via FAIR principles, of the suggested architecture to future scenarios.

In the following, relevant research papers will be discussed in the Related Work section. Next, we briefly present the context of our paper in order to describe the formalization process of the architecture design, followed by the description of the architecture of the DPP system using KGs and data spaces in Section 4. We also suggest our considerations in the discussion section (Section 5), also indicating future work directions, before we conclude in Section 6.

2. Related Work

The usage of data spaces for organizing a DPP system is advised by several papers [6, 7, 8, 13]. Several papers suggest using Administrative Asset Shell (AAS) [14] or blockchain as part of the solution design for DPP [7, 15, 16, 17, 18]. Several papers discuss ontologies for DPP [19, 20, 21]. In this paper, we focus on the usage of ontologies and KGs as an adaptable and flexible approach to structuring the DPP data asset. The work [22] provides an architecture design for a Digital Twin-based DPP for food products emphasizing the product traceability aspect allowed by DPP. Another approach to the traceability of products is provided in [23], where the authors discuss the role of Cyber-Physical Systems (CPS) and an Internet of Materials online platform in increasing the transparency of materials life cycle. The work [13] explores a DPP architecture for the footwear industry, focusing on the integration of data space principles and on the usage of W3C Decentralized Identifiers (DIDs). Building upon the previous work in [10, 11], this paper discusses how to use data spaces, ontologies and KGs to design an architecture for a DPP system. To the best of our knowledge a comparable architecture has not yet been discussed by a scientific paper.

3. Context

To formalize the architecture of our DPP system, we first examined the requirements for a DPP system [10], where we defined a setting that outlines a use case scenario for the DPP system. The use case scenario begins with a customer scanning a QR code on a product, which triggers the calculation of the carbon footprint generated during manufacturing of this product. The requirements were structured in seven groups: 1) product code scanning, 2) data exchange, 3) data representation, 4) carbon footprint calculation, 5) security, 6) logging, monitoring, auditing and compliance, 7) documentation and support. To meet the identified requirements, we suggested using Semantic Web technologies for the representation of the DPP data assets and presented a first version of the DPP ontology. Additionally, we considered using data spaces to exchange the carbon footprint information between an EO and its suppliers. In the present paper, we are focusing on the first four groups of the requirements for the initial architecture design, classifying them as functions of a minimal viable product within the context of a DPP system. On the way towards the initial architecture, we also walked through a case study at a furniture dealer and described the process of creating and issuing a DPP using data spaces and ontologies [11]. This way, the first version of the ontology [10] has been expanded to include 15 classes, 10 object properties, and 19 datatype properties, along with 331 axioms like `rdfs:subClassOf`, `rdfs:domain` and `rdfs:range`. Its structure integrates data from both the wood tracking and carbon emission calculation use cases.

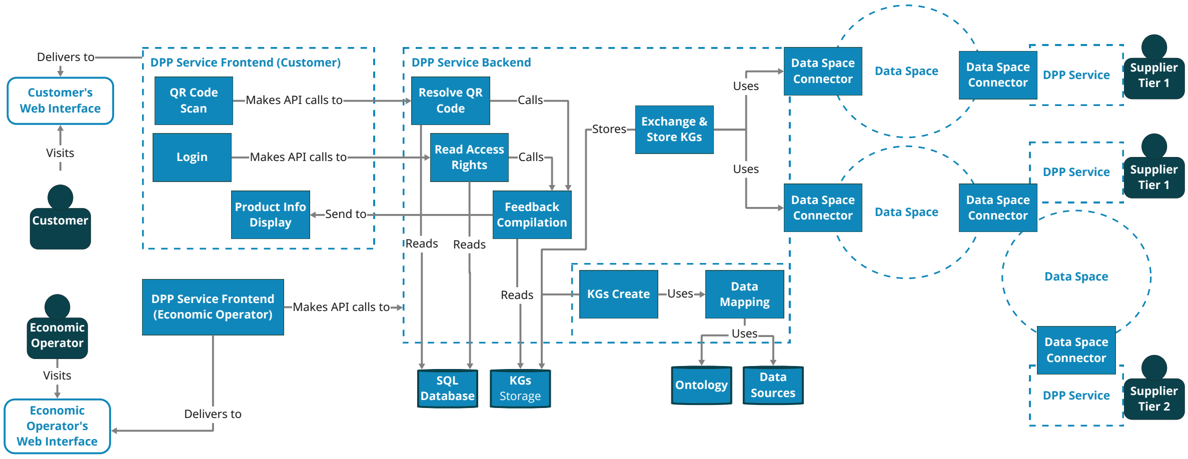

Figure 1: The initial architecture of a DPP system provides a detailed overview of the DPP service frontend for customers and the DPP service backend. Other components are presented at a higher level to offer a broader view of the entire DPP system. The architecture is formalized using the C4 model [24].

4. Architecture

In this section, we present the initial architecture design of a DPP system for product carbon footprint tracking using KGs and data spaces, see Fig. 1. We describe how the system can be used by an EO, its customers and suppliers. Direct suppliers of an EO are categorized as Tier 1, while those providing intermediate materials to the Tier 1 suppliers are categorized as Tier 2 suppliers. We used the C4 model [24] to visualize the DPP system architecture, employing the component level approach to represent the service backend and the customer's frontend, while using the container level approach to illustrate the remainder of the DPP system. By combining these levels, we intend to offer both an overview of the system and a more detailed view of the DPP service. We describe the architecture workflow, using product carbon footprint tracking as an example.

Additionally, in accordance with current legislation [3], EOs will be responsible for providing DPPs for their products at the point of market entry. Therefore, we assume that the DPP service frontend for EO's customers, along with the related backend, will be deployed by the EO (cloud solution or local infrastructure).

4.1. DPP Service Frontend for Customers

The DPP service frontend allows customers to scan a product's QR code and access information about the product, calculated in the backend. For example, if customers want to know the carbon emissions generated during the product's production, as well as the production of its intermediate components, they can view a summary in the Product Info Display section of the interface. Customers do not need to log in to the system to view basic information about the product. However, if controlling institutions, for example, require more detailed information about the product or the composition of its carbon footprint, they can log into the system to access a more comprehensive overview in the Product Info Display. Therefore, the DPP system must accommodate different levels of access rights. In our architecture, we propose storing and managing these access rights within the DPP Service Backend.

4.2. DPP Service Backend

In the backend, the DPP service uses an SQL database to store login credentials and manage access rights to the DPP data assets stored on the EO's premises. Furthermore, the SQL database also has information on how to attribute product IDs from the QR code to the related KGs. Using the information from the SQL database, the Feedback Compilation component reads KGs from the EO's storage and by traversing them, summarizes the necessary information. For example, information on the carbon footprint will be summarized using information from the corresponding KG of an EO, as well as KGs from all the suppliers who delivered the intermediate materials for this product. To achieve this, the ontology for product-related KGs is used to connect the product with its components. Thus, the KGs storage of an EO should provide both the KGs about its own product manufacturing process and KGs about (intermediate) product components from the EO's suppliers. We base our approach on the assumption that suppliers make carbon footprint information available upon product delivery, but may also provide updates at later point in time. The Feedback Compilation component calculates the carbon footprint for the individual products based on the up-to-date KGs when triggered by a customer's request.

To create KGs for production processes, the EO uses a corresponding ontology and relevant data sources. Through mapping languages and ontological terms, and executed via a mapping engine, the data sources are converted into triples and can be stored, for instance, in RDF format. The Exchange and Store KGs component triggers the collection of KGs from the suppliers using the functionality of data spaces.

4.3. Collecting Data from Suppliers

To collect data from suppliers, the EO uses a data space connector to establish agreements on data exchange and negotiate the associated policies. The data assets from suppliers are then transmitted to the EO in a peer-to-peer (P2P) manner, following the data space design. As a result, metadata about the data exchange between participants is recorded by the data space connectors, while the data assets themselves are exchanged securely. In terms of providing information on produced materials, suppliers are also playing a role of the EO in B2B. Therefore, the components from the DPP Service Backend of an EO should be deployed for their suppliers as well. These components should assist with compiling summarized information about produced materials, creating KGs based on the suppliers' data sources and providing them to the EO using data space functionality. Suppliers of Tier 1 should also have components to collect DPP data assets from their suppliers, which are mentioned as suppliers of Tier 2 in the Fig. 1.

4.4. DPP Service Frontend for an EO

To effectively manage the DPP service backend, the EO should also have a separate DPP service frontend, distinct from the one used by customers. This frontend should enable the EO to initiate data exchanges with suppliers and begin the process of mapping data sources to the KGs. Additionally, it should allow for updating access rights in the SQL database and managing the relationship between a QR code and data represented in the KGs. Suppliers should also have their own dedicated DPP service frontend.

5. Discussion and Future Work

The initial architecture presented in this paper is based on the previous work [10, 11] on the DPP in the wood processing industry. The scope and the limitations of the use case scenarios attributed to business processes in this industry also extend to the architecture design in this paper, as the architecture design was not investigated when applied to use cases in other industries. Hence, to confirm generalizability of the suggested architecture, further research is needed to test the architecture's applicability in other domains.

Additionally, while carbon footprint was used as an example for this architecture, the compilation of the information in the backend of the service should also be tested for further data sets, as it may bring more considerations on the components for the backend.

Among further possible improvements is the introduction of greater granularity for the DPP information. For example, information about a product should include not only manufacturing information, but also information on product repair. Information from recycling companies can be helpful for the product-related analytics from the EO's perspective. Exploring how to integrate such data into the DPP service will be an important area of future work, as repair or recycling information should be reflected in the product DPP after an EO releases the product to the market.

The current architecture design includes data mapping functionality, however it is also important to extend the backend with SHACL rules for validating the structure of KGs.

6. Conclusion

The DPP is a crucial tool in advancing sustainability efforts: by providing essential data on the origin, composition, and environmental impact of products, the DPP facilitates Circular Economy practices and supports the global transition to more sustainable production and consumption patterns. This paper presents an initial architecture for a DPP system using data spaces and KGs to manage and exchange product data, with a focus on tracking carbon emissions as a key example. The proposed architecture is designed to be flexible and scalable, allowing it to adapt to future scenarios through the use of KGs and supporting distributed data sharing through data spaces.

Future research will focus on refining the system and expanding its components to support additional use case scenarios for collecting and presenting DPP information, such as material tracking or hazardous materials, as well as information on product repair and recycling.

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Declaration on Generative AI

During the preparation of this work, the author(s) used GPT-4o LLM in order to: Grammar and spelling check. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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