Bringing the Digital Product Passport to Life: Requirements Analysis for a Carbon Footprint Tracking System Using Knowledge Graphs and Data Spaces

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ABSTRACT

Inspired by the Sustainable Development Goals of the United Nations, the European Union (EU) has taken numerous regulatory measures to realize a low-emission circular economy (CE). In particular, the EU is advancing the idea of the Digital Product Passport (DPP) to promote data sharing between organizations and improve the environmental impact of products on the basis of the data. Although the exact requirements for the content of the DPP are yet to be defined, the global climate agenda suggests that across all product groups the carbon footprint will be an important part of the DPP. Due to its broad application, the DPP must not become a market entry barrier for companies or interfere with existing value chains. Technologies for the DPP must be affordable and accessible to companies, regardless of their economic and geographical focus. Recent research concurs that the usage of data spaces to manage the DPP system facilitates the secure exchange and easy linking of data. However, there is still no consensus on what information the DPP should contain. In this paper, we analyze the requirements that a DPP system must meet, discuss the role that the combination of knowledge graphs and data spaces could play, and outline their potential using the example of tracking the carbon footprint of products. The results create a basis that may considerably facilitate the future implementation of DPP systems.

CCS CONCEPTS

• **Information systems** → *Enterprise applications*; *Information systems applications*; *Enterprise information systems*;

KEYWORDS

Digital Product Passport, Data Spaces, Ontology, Knowledge Graphs

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1 INTRODUCTION

In alignment with the Sustainable Development Goals in various sectors [3], the European Union (EU) has established a set of policies under the Green Deal [12] and an action plan [13, 14]. Both are designed to coordinate the efforts towards a sustainable economy without inhibiting multifaceted cooperation among stakeholders, e.g., by increasing market entry barriers. In transitioning to a sustainable economy, EU decisions promote the optimization of current production and consumption practices while also integrating novel approaches [14]. Collection and analysis of data about production and consumption processes will play a pivotal role in this transition. For instance, in the context of the economic sustainability goals of the EU, the reduction of carbon emissions remains a critical component of the EU climate targets [5]. Given the significant carbon emissions of manufacturing processes, the collection and analysis of carbon footprint data is of great importance. As a result of EU initiatives [15], the manufacturing industry will have to provide its customers with data on the carbon footprint, in addition to other product parameters, as part of a Digital Product Passport (DPP).

The DPP is a novel instrument towards a more sustainable economy, defined as providing "information on the origin, composition, and repair and disassembly possibilities of a product, including how the various components can be recycled or disposed of at end-of-life" [19]. The DPP is a decentralized framework for collecting, summarizing, and verifying product data. Following the DPP idea, each product should have a unique identifier that links a particular product to its DPP. Some parts of a DPP may have

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access restrictions to protect proprietary information about manufacturing processes [16]. Product-specific DPPs will be regulated by Delegated Acts of the EU Commission. Examples of such product groups include textiles and footwear, iron and steel, furniture, etc.

Given its original intent, the DPP should be integrated into existing manufacturing processes with as little environmental and economic impact as possible. From an environmental point of view, computational resources for the implementation of the DPP should be considered [21]. From an economic viewpoint, the introduction of the DPP should not negatively influence existing manufacturing value chains, e.g. companies should not be limited in their choice of suppliers due to DPP-related concerns. At the same time, a framework for the DPP should be adaptable to and scalable for new use case scenarios [21]. To meet these requirements, designing a DPP within a manufacturing data ecosystem across heterogeneous value chains with data spaces is a commonly suggested approach [8, 21, 22]. A data space is an abstraction of a distributed data management system across different parties, which employs a (centralized or decentralized) metadata registry and secure data exchange channels to accommodate a scalable data sharing environment with defined data management policies [7, 11, 17, 24]. Data spaces allow cooperation between and data exchange among participants of a value chain, regardless of their underlying infrastructure. While providing an interface for flexible metadata management about exchanged data, the data space concept strives for secure data exchange among participants in a peer-to-peer (P2P) manner.

To reduce the risk of greenwashing, DPP claims should be substantiated through verified authorship of data records [6]. Data spaces provide mechanisms for recording metadata about data exchange transactions including the identity of participants. These metadata, however, do not include enough information to summarize product records collected across value chains, as the data space has no insight into the content of the exchanged data. Moreover, the data from which the summarized carbon footprint has to be drawn is heterogeneously structured. The challenge does not only lie in the format but also in the semantics, as data records with different structures and different scopes of carbon emissions, e.g., transportation, production, and recycling, should form a unified DPP. Structured frameworks for organizing information, such as ontologies, are well suited for the conceptualization of domain knowledge as they provide a common vocabulary to annotate data for machine interpretation. An ontology for a value chain and knowledge graphs (KGs) with corresponding participant data can help to tackle data heterogeneity [10] as it is found in the context of the DPP. To the best of our knowledge, a comprehensive requirements analysis of an ontology for a DPP in a value chain is either unavailable or still under development. Additionally, despite several works in this field, the use case where stakeholders are connected to multiple data spaces has not yet been considered.

In this paper, we first present our methodology for eliciting requirements for a DPP system (Section 2). In particular, we review information from the perspective of four research questions (including a literature review, Section 3) to draw baseline assumptions. Building upon these assumptions, we formulate requirements for a DPP system for tracking the carbon footprint of products (Section 4) and present an example DPP system design (Section 5). In contrast to existing work, we consider (1) a scenario with multiple data spaces within a value chain and (2) the implementation of DPP data assets using an ontology. We use a value chain ontology to provide a comprehensive overview of the concepts in data records from different parties, additionally describing interconnections between them in the form of a KG. Future work will extend to the implementation of a demonstrator of a DPP system and its evaluation. We suggest a preliminary evaluation and discuss possibilities of extending our work (Section 6) before we conclude (Section 7).

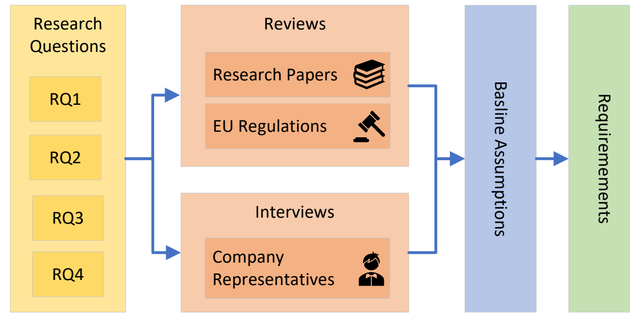

Figure 1: Structure of the methodology. Baseline assumptions drawn from EU regulations, literature review, and interviews, together form the basis of the requirements.

2 METHODOLOGY

As shown in Fig. 1, the methodology for eliciting and analysing requirements for a DPP system carbon tracking incorporates several main steps. First, we reviewed existing EU regulations [12–15] related to DPP. In addition to this review, a literature review is conducted to help us understand the state of the art in DPP development and implementation, the challenges and what lessons can be learnt. The two reviews are supplemented with structured and semi-structured interviews with representatives from four companies (three in Austria and one in Germany) in the wood processing industries. The purpose of the interviews is to develop and in-depth understanding of the current state of the underlying infrastructure for implementing the DPP in specific (wood processing) industrial settings.

To guide the reviews and the interviews, we factored in the following research questions:

- RQ1 What requirements for the DPP are defined by the current state of EU legislation?
- RQ2 Given the current state of the infrastructure and communication mechanisms of participants in the value chains, is there a need to design a novel technological solution for the DPP?
- RQ3 Which steps have to be taken to unify data currently exchanged across value chains for use in common DPP data assets?
- RQ4 Are data spaces appropriate and beneficial for the exchange of DPP data?

In response to these research questions, we identified the following baseline assumptions for defining the requirements for the DPP. For RQ1, we found that although exact requirements for the DPP contents will be defined in upcoming EU regulations, following the global climate agenda, it is most likely that carbon emissions will be an important part of the DPP for all product groups. The carbon footprint is therefore a key piece of information in our DPP data asset. We addressed the RQ2 with the interviews with industry representatives. Since each of the four companies specialises in a unique product within the wood processing industry, a separate questionnaire was administered to each company. Each questionnaire consisted of different sections with different number of questions. For instance, the questionnaires covered sections like Data about materials in the storage, Data about production processes and several others. All sections were designed to understand the product-related data flow and the infrastructural solutions supporting it. The interviews regarding RQ2 revealed that the underlying infrastructure of the participants in the value chains is heterogeneous, which underlines the need for a novel technological solution for the DPP.

The investigation towards RQ3 showed the heterogeneous structure and format of currently exchanged data across value chains, as well as heterogeneous communication mediums between participants. To adapt to the heterogeneity of the exchanged data and facilitate the adaptability of the DPP to new use cases, our requirements include the use of ontologies and KGs for modeling DPP data assets. With respect to RQ4, our findings suggest that the DPP has to be implemented in a decentralized framework [18, 19]. Thus, data spaces are suitable to meet the DPP requirements. Further finding from our literature review are presented in the next section.

3 RELATED WORK

In the following, we summarize works that consider requirements for the DPP. Many authors discuss requirements for the DPP in general terms [23, 27, 32] and demonstrate its benefits [35]. From a technical perspective, several works recommend using the Asset Administration Shell (AAS) [4] as an infrastructural solution for collecting standardized DPP data sets from production machines [8, 9, 26, 28]. However, the need to invest in suitable IT infrastructure to support AAS was identified as a challenge [8] and raises the market entry barrier for small companies. Many researchers discuss the usage of a blockchain for the unique identification of manufactured goods as part of DPP or circular economy approaches [20, 25, 29, 33]. For exchanging information across participants in a value chain, various researchers advise the usage of data spaces [8, 28, 30, 31, 34]. This paper analyzes the requirements for a DPP system leveraging data spaces and KGs. It aims to propose a solution for those value chain participants, who do not need to utilize AAS in their production processes and seek to lower computational costs associates with blockchain technology.

4 REQUIREMENTS

In this section, we outline the requirements for a DPP system that tracks the carbon footprint caused while manufacturing a product from composite material, including its final assembly. During the formulation of the requirements, we were cross-referencing them with existing DPP-related EU regulations [12–15] , ensuring consistency and drawing guidance from these regulations. The final assembly of a product is happening on the premises of an *economic operator*, who is "placing the product on the market" [15]. Therefore, we consider the economic operator to be a company that prepares the product in its final form (for sale to individual customers), from intermediate materials provided by several wholesale suppliers. Suppliers provide intermediate materials of different types and may also have their own suppliers. An economic operator and the suppliers of all intermediate materials are forming a product value chain. The economic operator is responsible for providing individual customers with a summarized product carbon footprint in the form of a DPP [15].

Our requirements are informed by the baseline assumptions outlined in the methodology section. In particular, we accommodate the heterogeneity of exchanged data and enhance the adaptability of the DPP to new use cases by including the utilization of ontologies and KGs in our requirements. As a decentralized framework for data exchange, we operate under the assumption of data spaces. The DPP system should accommodate various users, each with distinct access rights to DPP-related information based on their roles. An economic operator, responsible for issuing the DPP, should be able to request the information from other value chain participants and compile the final DPP for customers. Customers should have access to the necessary DPP to make more environmentally conscious purchasing decisions. In the following, we present the requirements for the DPP system grouped by functionality, considering different roles of the users.

4.1 Product Code Scanning

The system should provide a user-friendly interface for customers that allows them to scan a product code with the camera of a smartphone or tablet. This interface serves as a starting point for customers to begin the discovery of the carbon footprint using individual product codes. Therefore, the following requirements should be met by the DPP system:

(1) The product code should be presented graphically to facilitate customer interoperability with the DPP system and eliminate the need to enter longer numerical codes manually.
(2) Provide a web interface with components which customers can use to scan the code of the product before or after purchase. The web interface should be hosted under the domain of the economic operator.
(3) The web interface should verify the format of the code, translate it into an ID of the product and send the ID to the back end.

4.2 Data Exchange

The overall design of the system includes data spaces for secure data exchange between the economic operator and the suppliers involved in the value chain.

(1) Data spaces should provide an application programming interface (API) to search for the suppliers using their IDs.
(2) The data spaces should provide an interface where the value chain participants can see metadata about negotiations of the data exchange between them, alongside with metadata about access policies, data management plans and data governance.
(3) When the data exchange negotiations between the value chain participants are completed, data spaces should support the establishment of a secure communication channel

between the participants to exchange the DPP records in a P2P manner.

(4) The identity of the participants of data spaces should be verified by the providers of the data spaces.
(5) Data spaces should allow the exchange of DPP records only from authorized and verified participants.

Additionally, all participants of the data spaces should be able to use a connector certified by the International Data Space Association (IDSA) [2] that offers the functionality required for secure data exchange, e.g. the Eclipse Dataspace Connector (EDC) [1].

4.3 Data Representation

To facilitate the seamless integration and retrieval of data, the following requirements for data representation have been identified:

(1) Enable local storage of data using the proprietary format of each participant.
(2) Allow the integration of different data sets, each possibly following distinct proprietary formats, to obtain comprehensive data for the DPP of a product.
(3) Support the transformation of integrated data to ensure accurate interpretation by all participants.
(4) Improve the interpretation of the resulting DPP for consumers.
(5) Ensure the extensibility of the data schema for domain-specific applications.
(6) Enrich the output with contextual information such as geographical data and regulatory requirements. This additional context enhances the understanding of the product value chain and facilitates more accurate analysis and decision-making for both customers and producers.
(7) Assure the quality of the output by validating the accuracy, completeness, and consistency of the DPP records.

To meet these requirements, we consider a potential solution based on Semantic Web technologies, specifically utilizing an ontology and a KG. We note that mappings to a KG (e.g., RML https://rml.io/specs/rml/) allow us to use any structured data source regardless of its format (satisfies 1). Furthermore, KGs enable data merging (satisfies 2) and data conversion (satisfies 3). Ontologies facilitate data extensibility (satisfies 5) and provide semantic descriptions of data points (satisfies 4). Additionally, leveraging external Linked Open Data (https://lod-cloud.net/) allows for data enrichment (satisfies 6). Lastly, various shape constraint languages (https://www.w3.org/TR/shacl/, https://shex.io/) enable the validation and repair of the RDF data (satisfies 7).

We have developed an initial draft of the DPP ontology supporting our use case of tracking carbon emissions, as depicted in Fig. 2. This ontology includes two key classes essential to our use case: the "Production" class, which represents the production process, and the "Material" class, which encompasses the subclasses "Raw Material" and "Product". Materials are utilized in the production of other materials, which means they can serve as end products or as components/constituents of other products. Materials are characterized by their measured parameters ("Parameter"), ensuring the desired quality. Production processes are linked to environmental impacts ("EnvImpact") such as carbon emissions ("CO2Emissions"). Materials are linked to other materials with the relation "isUsedToProduce"; this relations enables tracking of individual materials and allows storing information about which intermediate materials were used to produce a composite material.

To represent a production process for a product with components, one would begin with raw materials that are involved in a production step (via the "isUsedIn" relation) to create an intermediate product. This intermediate product, potentially along with additional raw materials and/or other products, is then utilized in subsequent production steps to generate another product, and so forth.

4.4 Carbon Footprint Calculation

Using the DPP KGs stored on the economic operator premises, the system reconstruct available KGs to calculate the final product carbon footprint.

(1) The system should be able to retrieve all records about carbon emissions from the collected DPP records.
(2) The reconstruction of the available KGs should ensure that the latest updates of information received by the economic operator are incorporated into the KGs.
(3) The system should be able to calculate the carbon emissions per product based on the data on the carbon emissions per batch of intermediate product. For this purpose, the system should have information about exact volumes of the intermediate materials per product.
(4) The system should also be able to calculate the carbon emissions based on the DPP records of suppliers that have their own value chain. These suppliers should provide the economic operator with the carbon emissions per batch of the intermediate material. Therefore, the carbon emissions should be pre-calculated by the suppliers with their own value chain using their own instance of the DPP system. Alternatively, these suppliers should include guidance on how to calculate the carbon emissions per unit of their materials when collecting the DPP records from their value chain.

To meet the requirements, the environmental impacts ("EnvImpact" class in the ontology) of the production process would include information about carbon emissions (denoted by the "CO2Emissions" class). The chain of materials → production → materials → . . . enables the retrieval of carbon emissions throughout the entire production line, thereby satisfying requirement (4).

4.5 Security

Reliable security measures should be implemented to protect the confidentiality and integrity of the data exchanged between the system participants. Access control, encryption and authentication mechanisms should be used to ensure data security.

(1) The implemented security measures should ensure that all participants of the system comply with them, but still can easily access the necessary data samples. Compatibility issues for DPP records obtained from different sources should be avoided.
(2) The system should enforce data integrity checks to prevent tampering or unauthorized changes during transmission.

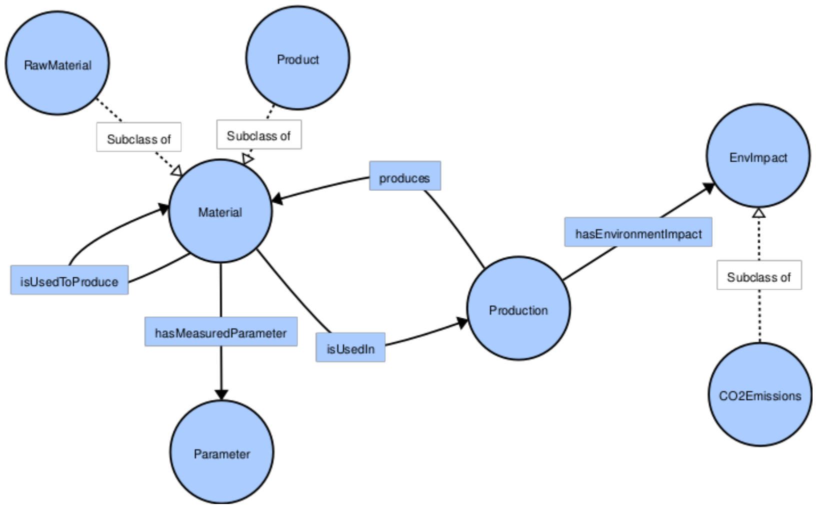

Figure 2: First version of the DPP ontology. Blue circles represent classes and arrows represent relations between classes.

(3) The system configuration should ensure that information that may constitute a trade secret cannot be subsumed from the DPP records.
(4) The system should have defined access control policies to regulate data access based on user roles and authorizations.

4.6 Logging, Monitoring, Auditing and Compliance

Comprehensive logging and monitoring mechanisms are required to track user interactions, system activities and performance metrics. Logs should be retained for audit purposes and real-time monitoring, allowing administrators to identify and resolve issues within a reasonable time frame.

(1) The system should have logging mechanisms to track user interactions, data retrieval processes and system activity for auditing and troubleshooting purposes.
(2) The performance and resource usage of the system should be monitored to identify potential bottlenecks and optimize system efficiency.
(3) The system should provide logging and auditing capabilities to track communication errors and facilitate troubleshooting.
(4) The system should maintain comprehensive audit logs of all interactions and data exchanges within data spaces to ensure compliance with rules and regulations.
(5) The system's audit logs should capture relevant metadata such as timestamps, user identities and actions taken.
(6) The system should facilitate audits and compliance reporting by providing tools and utilities for log analysis and export.

4.7 Documentation and Support

Given the complexity of the DPP system, its users need guidance to navigate all its functionality.

(1) A comprehensive documentation for users and administrators on how to use the interface, interpret carbon footprint data and troubleshoot common issues should be provided.
(2) The system should provide technical support channels for users and administrators to seek help and resolve questions or issues.

In the next section, we present an example DPP system design that meets the defined requirements.

5 SYSTEM DESIGN

In the following, we describe an example DPP system design, as depicted in Fig. 3. The DPP system consists of a front end where individual customers can scan a unique QR code attributed to the final product, send a request for a summarized carbon footprint to the economic operator and receive the footprint in a summarized form. The front end with its web interface is deployed on infrastructure of the economic operator. Customer requests are processed in the back end of the economic operator. The front end and the back end together form the economic operator's DPP service.

Upon receiving a new request from a customer, the individual ID of the product, which was encoded in the QR code, is matched to the available information stored locally within two steps. First, the ID is compared to records in a local Database Management System (DBMS), e.g. MySQL or PostgreSQL. In these records, information about batch IDs of all intermediate materials from the respective suppliers alongside with the names/IDs of the suppliers is stored. Second, using the same ID, the back end checks the information about carbon emissions created during the production of the final product by the economic operator. This information is stored in the storage of the economic operator in the form of a KG, e.g. in RDF format. This KG is created from the relevant data points, such as carbon emissions in kilograms, based on the general ontology for the DPP data asset.

To communicate to the suppliers about necessary data exchange, the DPP service uses a dedicated data space. The economic operator connects to the data spaces shared with direct suppliers to establish P2P connections with those suppliers. In Fig. 3 these suppliers are depicted as connected in parallel to the economic operator's data space, in line with the perspective of the value chain, where they

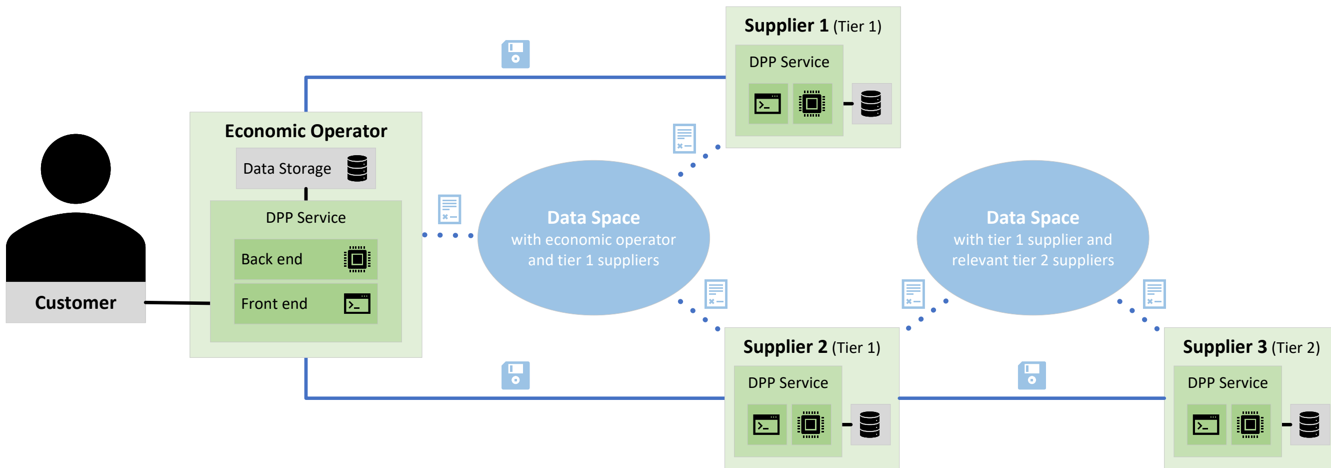

Figure 3: DPP system design with data spaces involving an economic operator responsible for delivering carbon emissions to an individual customer for a specific product. Using data spaces, the economic operator communicates with its suppliers to collect the DPP KGs with the carbon emissions data of the products via P2P channels. The dashed blue lines represent the exchange of metadata, the solid blue lines represent the P2P data exchange.

provide materials of different types at the same stage of the product manufacturing process. The suppliers may produce their material without consuming any further components from their own value chain, as for example, Supplier 1. In this case, they should just share the carbon footprint from their side using the DPP service deployed on their premises with the economic operator. In case a supplier has its own value chain, as for example Supplier 2, it is responsible for collecting the carbon emissions from the rest of the value chain. For this purpose, suppliers may use a separate data space, which connects them to the next direct participant of the value chain. In Fig. 3, Supplier 3 is such a participant.

Exploring the DPP system design example helped us uncover additional requirements, presented next.

5.1 Processing of the ID from the Product Code

Upon receiving the QR code and translating it to a product ID, the DPP service of the economic operator uses this ID to extract further information about the product. This information includes IDs of the batches of the used intermediate materials, as well as IDs/names of the suppliers of these materials and IDs of the data spaces for the communication with the suppliers respectively. Hence, we identify the following requirements:

(1) In the back end, the product ID from the code should be connected to the information about suppliers of intermediate materials, batch IDs of materials, as well as the suppliers' IDs/names and respective data space IDs.
(2) The system should store the IDs of the data spaces such that it is possible to resolve them within a request to a network address of the data space API. The same holds for the suppliers' IDs.
(3) As names of the suppliers can changed due to legal name amendments, the IDs information should be stored in a dedicated storage rather than a product-related KG.
(4) The ID from the code should also lead to a KG with information about carbon emissions from the product manufacturing processes of the economic operator. This KG should be stored on the premises of the economic operator.

For requirement (3), since updating a supplier's ID or name should be straightforward, a DBMS is a better fit than a KG. Updating all KGs for every product can be a tedious task prone to errors.

5.2 Identification of Outstanding Information and its Collection

The DPP system should be able to identify the direct suppliers of the intermediate materials based on the product data stored at the economic operator's premises. Therefore:

(1) The DPP system should be able to identify the situations when a product-related KG is complete or when additional information should be gathered from other value chain participants.
(2) The system should be able to identify situations when locally stored information is insufficient to request outstanding information from the suppliers or insufficient to identify if the locally stored DPP KG is complete.
(3) The system should be able to take the batch IDs of the intermediate materials and initiate the request for the DPP data from the suppliers for these batch IDs. This should be done using the IDs of the suppliers and related data spaces.

In summary, the described system should be used as a tool for customers to track and compare product carbon footprints, promoting transparency and sustainability in the production and consumption of goods. By combining the technologies described above, the system enables informed decision-making and promotes environmentally conscious production and purchasing behavior.

6 DISCUSSION

While eliciting the requirements of a DPP system to track product carbon footprints, we continuously compared them to the existing requirements of the EU regulations. These comparisons allowed us to identify the requirements that align with the regulation [12–15]. From the interviews we learned that current practices involve exchanging product information via emails (often as PDF attachments) or using paper-based methods. Exchanging DPP records in structured form, KGs in our design, enables easier data analysis and a wider range of analysis techniques compared to PDF representations.

The ontology suggested in the requirements overview (Section 4) can be expanded to accommodate an exchange of further information about a product between value chain participants. Such information can be, for example, information about recycling conditions of a product. In case of extending the ontology to accommodate for a business-sensitive exchange of the information, a DPP system should have clearly defined access rights to every part of the data inside the company of an economic operator, as well as in the DPP data ecosystem.

7 CONCLUSION

EU regulations emphasize the need for sustainable practices in manufacturing industries. One key instrument for achieving this goal is the DPP. The DPP should incorporate product-specific information such as origin, composition, repair and disassembly possibilities, as well as the product carbon footprint. Our research focuses on the DPP's role in tracking carbon emissions across various industries. Based on the analysis of the existing literature and DPP-related EU regulation, as well as the analysis of interviews with wood processing industry companies, we identified baseline assumptions:

(1) the exact requirements to the DPP content are not yet defined in the EU regulations;
(2) data spaces offer a solution for organizing communication within value chains, as highlighted in prior research;
(3) ontologies and KGs address data heterogeneity across value chain.

Building upon these assumptions, we developed specific requirements to the DPP system and introduced an initial ontology for carbon footprint DPP records. Additionally, we presented a system design and discussed further requirements that emerged during the modeling process. Finally, we discussed benefits of the suggested design over existing solutions and explored possibilities for future extension.

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