Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 58-19 (2024) 235–240

Realizing Closed-Loop Supply Chain Networks based on Dataspaces and Manufacturing Marketplaces

Leonhard Kunz * **Manuel Reif** * **Teresa Petzsche** *
Anne Schmallenbach * **Christiane Plociennik** *
Martin Ruskowski *

* *German Research Center for Artificial Intelligence, Trippstadter Straße 122, 67663 Kaiserslautern Germany (e-mail: author@dfki.de).*

Abstract: Circular economy strategies, driven by national and EU regulations and market demand, are reshaping the manufacturing industry towards sustainability and resilience. Closed-loop supply chains, integrating secondary materials, aim to minimize waste and carbon footprint while enhancing supply chain flexibility. Leveraging online B2B marketplaces, manufacturers, suppliers, and other stakeholders engage in dynamic networks, optimizing resource utilization through competitive service offerings. This work explores the integration of stakeholders across the product lifecycle into a digital marketplace with secure data exchange, following IDSA and Gaia-X concepts. It highlights the Digital Product Passport's (DPP) role in sharing product data throughout the product lifecycle. DPP and service offerings are realized using the Asset Administration Shell. Implemented in the SmartFactory^{KL} demonstration environment, it showcases circular process adoption and carbon footprint reduction through a service-oriented marketplace.

Keywords: Information Sharing, Sustainable Supply Chain, Closed-loop Supply Chains, Circular Economy, Value Networks, dataspaces, Asset Administration Shell, Digital Product Passport

1. INTRODUCTION

Driven by the necessity to preserve resources and reduce the environmental impact in the production and consumption of goods, the establishment of a more sustainable economy is indispensable. The transition into a circular economy stands in the center of these efforts.

Policymakers in the EU have created the legal framework to facilitate this development with the European Green Deal, which was operationalized in the Circular Economy Action Plan in 2020. It explicitly states substantial material savings throughout value chains and production processes as one of its prime targets (European Commission, 2020). Another important document is the Ecodesign for Sustainable Products Regulation (ESPR, European Commission (2022)), which outlines the Digital Product Passport (DPP), a concept to store product-related information. It aims to develop standards for the information that needs to be provided about a product throughout its production chain and the following lifecycle (Götz et al., 2022). It is supposed to promote supply chain transparency, support informed consumer decisions and aid the improvement of decisions and processes at the end of the product's first lifecycle.

The conceptual framework for the formation of circular lifecycles of products, components and materials is provided by the R-strategies (Potting et al., 2017). The most important R-strategies are depicted in Figure 1. They describe the reprocessing of products that have reached the end of their use phase and their reintroduction at various points in the product lifecycle.

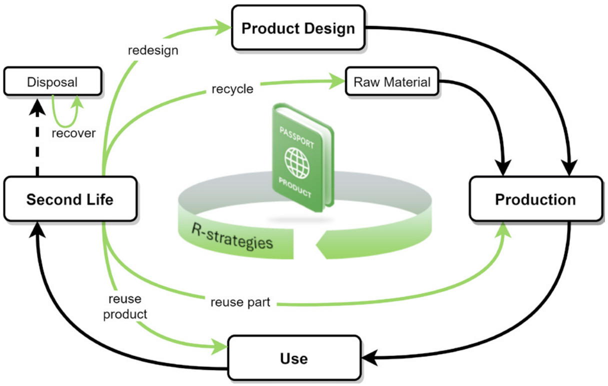


Fig. 1. The Digital Product Passport as a lifecycle overarching data node

A key challenge here is the diverse quality of the recovered components in the reverse supply chain makes. Digital B2B marketplaces for demand-supply matching attempt to close this gap by dynamically connecting suppliers and manufacturers on a per-contract basis under individual considerations (Berg and Wilts, 2019).

Secure data exchange between the partners does not only play a pivotal role in the negotiations following the matchmaking on these platforms. It is also a decisive aspect in

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2024.09.177

the decision-making for the further lifecycle path of the product and its components by the current owner of the product. This concerns, for example, the communication between companies concerning quality standards or the impact of damage on the product function (Rilling et al., 2023).

Decentralized dataspaces offer one way to implement such secure and trustworthy data exchange between companies. They build on the idea of matching decentralized data sources rather than integrating data into a centralized information framework (Franklin et al., 2005). This also allows the data owner to control the complete data sharing process, therefore guaranteeing data privacy and sovereignty. Politically, this approach is advanced by the Gaia-X initiative, which aims to develop a data infrastructure that conforms with European values of transparency, openness, data protection, and security (Gaia-X European Association for Data and Cloud, 2022).

In the following, we describe a concept and implementation that integrates all of these ideas. We describe a marketplace built on the concepts of Gaia-X that connects Original Equipment Manufacturers, suppliers and actors of the second life phase and integrates the forward as well as the reverse supply chain in a dynamic value network. It enables the parallel offering of products and manufacturing services. The concept also describes data exchange using an implementation of the DPP based on the Asset Administration Shell (AAS, Plattform Industrie 4.0 (2022)).

This paper is structured as follows: Section 2 discusses relevant work. Section 3 then introduces the concept of a marketplace-based environment for supply chain collaboration. Section 4 shows the implementation in a practical use-case at the *SmartFactory*$^{\mathrm{KL}}$. Section 5 presents the conclusion and outlook for further work.

2. RELATED WORK

2.1 Marketplaces for Circular Value Networks

B2B marketplaces matching suppliers for secondary materials, goods and services play a decisive role as enablers of a digitized circular economy. Berg and Wilts (2019) analyze the current deficits in supply markets to take up circular economy practices and discuss the potentials of digital platforms as an enabler. They identify information deficits on the quality of secondary materials leading to a lack of trust in these material streams as one of the central issues. de Jong and Mellquist (2021) underscore this perspective in their analysis of the business case of several platforms and manufacturers in the plastics industry. They attribute this, among others also to a lack of data from product tracing.

There is a discussion around the interaction of the stakeholders on B2B-marketplaces for closed-loop supply chain formation. Yet, many publications focus their discussion mainly on the aspect of the matchmaking between supplier and buyer as an essential part of the decentralized and heterogeneous nature of the materials offered on these platforms (Łękawska-Andrinopoulou et al., 2021). Often times, the conditions under which stakeholders are willing to share possibly sensitive information, that would increase the trust in secondary material streams is neglected (Berg and Wilts, 2019).

Rilling et al. (2023) discuss here the role of decentralized dataspaces and as a backbone for a trusted and interoperable data exchange on B2B marketplaces. This paper can be seen as an implementation and concretization of those aspects.

2.2 Digital Product Passport

The DPP is seen as another crucial tool for information exchange across companies, supposed to promote a digitalized circular economy (Adisorn et al., 2021; Walden et al., 2021; Jansen et al., 2023). The aim is to create a consistent lifecycle record about individual products with the aim to increase transparency along the supply chain, for example regarding the individual carbon footprint (Götz et al., 2022). The battery passport currently being developed is the first DPP mandatory for a specific product category (European Commission, 2022). Included are general product information, technical specifications, material composition specifications, sustainability indicators, instructions, and utilization information (e.g.: product condition/wear) (Battery Pass Konsortium, 2023). Significant benefit regarding the circularity of a product can be achieved when this record is collaboratively enriched with data throughout the manufacturing, usage and end-of-life phases (Koppelaar et al., 2023).

The distributed nature of this data across several stakeholders along the lifecycle requires an infrastructure for trustworthy and secure data exchange (Berg and Wilts, 2019). Rilling et al. (2023) propose a network of digital twins in their idea of a dataspace for the circular economy. They follow authors like Pourjafarian et al. (2023) and Plociennik et al. (2022) who demonstrated the utilization of the AAS for that. This approach stands in a whole line of initiatives to create the infrastructure for the DPP of which (Jansen et al., 2022) give a topical overview. This paper utilizes the approach of Pourjafarian et al. (2023) with its seamless integration into the Shared Production (SP), which will be further elaborated on in the next section. It extends the environment with the interaction of the DPP and a digital platform for supply chain formation to gain a gapless lifecycle record which results from the manufacturing phase.

2.3 Shared Production

SP describes a collaborative environment in which a federation of trusted partners share manufacturing resources through service offerings described with standardized digital twins over the lifecycle of a product (Bergweiler et al., 2022). The concept builds on an architecture Skills, Capabilities and Services (Diedrich et al., 2022), which automate processes from the field level over the factory control level up to intercompany coordination (Volkmann, 2024). Jungbluth et al. (2023) propose an architecture for the cooperation of businesses offering and requesting services.

Their implementation facilitates Gaia-X conformous dataspaces for trusted and secure data exchange to share possibly sensitive data necessary to enable requests of manufacturing services (e.g. CAD-files). Their architecture stipulates a marketplace to offer and request manufacturing services. During the manufacturing phase, product data is aggregated in a product AAS to form a digital twin of the product, spanning product data in the forward supply chain from cradle to gate (Simon et al., 2023). This paper picks up on this implementation and expands the SP concept to cover closed-loop supply chains and include services from the end of the product lifecycle.

In sum, the authors identified a research gap in descriptions of practical implementations that interlink the DPP and with marketplaces for dynamic supply chain formation in circular value networks. This paper will try to answer the research question of how supply chains can effectively be formed dynamically based on the trusted and interoperable data exchange in a network of digital twins.

3. CONCEPT

In this section, we present an extension of the SP ecosystem (Jungbluth et al., 2023) to represent closed-loop supply chains.

Participating lifecycle stakeholders from the end of the product use and collection phase in the ecosystem supports the gapless incorporation and documentation of transactions in the following lifecycle stages. By processing the transactions via the SP ecosystem, these actors can participate in the first-lifecycle supplier market and offer services directly to other suppliers in the ecosystem or Original Equipment Manufacturers.

Most of these services offered by the end of use actors (e.g. remanufacturing, refurbishing, etc.) can be treated similar to the manufacturing services (e.g. milling, 3D printing, etc.) that are already considered in the forward supply chain. These can be described using the *ServiceOffering* AAS Submodel described by Jungbluth et al. (2023). All services offered by the network participant are bundled together in a Submodel Collection *AssuredServices*. This factory AAS is provided to the network in a Gaia-X conform connector for the ecosystem dataspace.

This description of services is limited when an inventory of products with a different quality status are offered to the network. In the offer of a manufacturing service, the quality parameters of an individual product can only be shared after the service is completed. When components, that have already been manufactured, are offered again, the individual product's quality parameters are already known at the time of the service offering. Thus, a decision must be made as to which part from the inventory can be offered to the service requester.

Multiple approaches are considered, depending on which stakeholder of the offer processing the decision should reside with. A provider-centric approach locates the decision at the product provider, who decides which product from his inventory meets the requesters quality requirements. This requires an extensive description of the quality requirements, which might provide insights into design considerations for the product, and the requester might be hesitant to share this information. In a platform-centric approach, the platform itself performs a matchmaking between the provider and requester to match products from the provider's inventory to the requirements of the requester. This similarly involves the sharing of quality requirements by the requester to an outside party. It also requires absolute neutrality from the platform operator to ensure an equal market. A requester-centric approach can be considered as a third approach. Here the provider exposes their inventory of the products, they want to offer on the marketplace, to the requester. The requester performs an internal matchmaking to see if any of the products fulfil their need and quality requirements. This approach is considered to be the most favorable as it involves the least sharing of possibly sensitive data and therefore is pursued in the presented concept.

This paper therefore introduces a standard parts catalogue as an additional component to the Shared Platform ecosystem. This component resides at the connector of the service provider and lists the inventory that is offered to the marketplace. The catalogue is directly integrated in a new *ServiceOffering* to provide already existing parts and share their quality attributes.

For all approaches, a shared understanding of the product quality attributes is necessary. The product quality is therefore described in reference to a quality reference model known by service provider and requester.

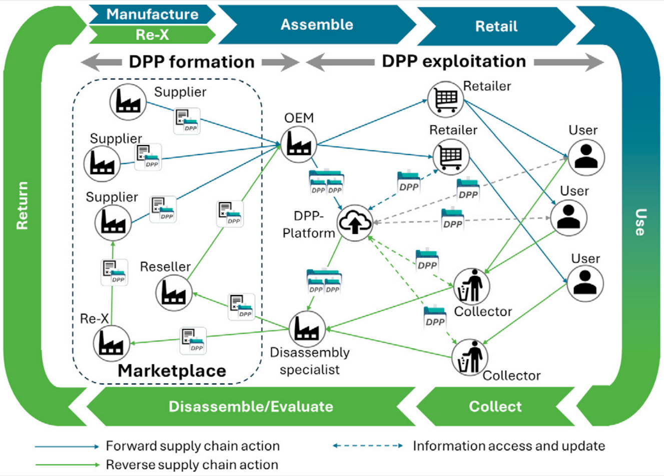


Fig. 2. Representation of closed-loop supply chains in SP ecosystem

The MaaS marketplace in this form can include some aspects of the closed-loop supply chain only indirectly. Especially interactions with the end-customer, when focussing on consumer products, cannot be properly incorporated as it would involve a direct participation of the customer in the marketplace. This would entail an interaction and setup with the necessary IT infrastructure.

We therefore propose an intertwining of the DPP concept and the information exchanged via the marketplace platform and gathered throughout the manufacturing process as shown in Figure 2. Simon et al. (2023) describe the process of manufacturing a product utilizing the SP ecosystem. During the production process data (e.g. CO_2-footprint, quality attributes, etc.) and part data (e.g. geometry, weight, etc.) are being gathered in the product AAS, which uniquely identifies an individual product. The product AAS of the individual components are being aggregated at the different production stages in separate product AAS by reference. In this way, a gapless information backbone including all components and processes belonging to an individual product is gathered during production and can then be provided in all subsequent lifecycle stages.

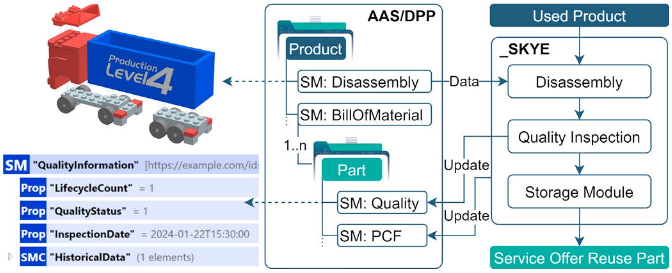
At this point, we introduce a storage platform to store this product AAS and manage access to the data. During the mid-life phase of the product, stakeholders can update and retrieve data according to their access rights. In this way, data from this lifecycle phase (e.g. product failures, repairs, scope 2 CO_2 emissions, ect.) can be collected, and the data utilized (e.g. assembly/disassembly information, contact information, ect.).

Once the product reaches the end of its use phase, it can be disassembled. The components can be reprocessed or resold. These transactions and processes can be represented in the marketplace by referencing the already existing product AAS with their lifecycle record. The existing product AAS can be referenced again when reusing a component in a new product in the assembly steps. The data from the mid-life phase can be used to cross-validate product quality status statements by the Re-X actor on plausibility. This increases trust in the quality of secondary products, encourages the reuse of already produced goods, and decreases the CO_2 footprint of a new product.

In this section, we proposed an extension to the SP ecosystem to represent closed-loop supply chains. It consists of the extension of service descriptions to offer already produced goods on a service marketplace. This part focuses on trusted and private data exchange. The second part is a description of the interaction of the marketplace and the DPP. A lifecycle record, which is as gapless as possible, increases trust in the statements communicated on the platform. An overview of the interaction of the systems is shown in Figure 2. In the next section, we demonstrate the concept on the example of a component reseller participating in the SP ecosystem and go more into detail on the adaptation of the marketplace.

4. IMPLEMENTATION

This section presents a use case for reusing parts of an example product as a service to establish CE in a dynamic manufacturing environment. The scenario demonstrates how a DPP based on an AAS can support the re-offering of quality-tested parts in the next lifecycle through a market-based contract manufacturing process. The use case is implemented on the vendor-independent demonstration and research platform of *SmartFactory*^{KL} which includes four production islands that form a SP ecosystem, simulating locally distributed production sites. Each island consists of Cyber-Physical Production Modules (e.g., additive manufacturing, milling, manual assembly) and logistics (e.g., collaborative robotics, individual shuttles, automated guided vehicles) with standardized interfaces. Capabilities, which describe encapsulated manufacturing processes that can be used in a uniform way, are offered as assured services at a marketplace using the Factory AAS for standardized description. The goal is to implement a Lot Size One production, exemplified on a fully customizable sample product, in this case a model-sized truck. The production sequence relies on appropriately parameterized capabilities offered at the marketplace. This reduces the need for specific resource configurations in one production site or in-depth expert knowledge of individual machines and processes.



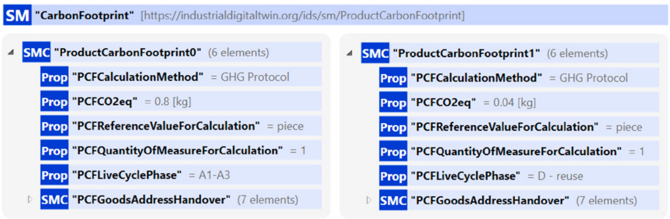
SM "QualityInformation" [https://example.com/ids
Prop "LifecycleCount" = 1
Prop "QualityStatus" = 1
Prop "InspectionDate" = 2024-01-22T15:30:00
SMC "HistoricalData" (1 elements)

Fig. 3. Procedure of reuse service at the production island *_SKYE*

Extending the demonstrator beyond the production phase, the new production island *_SKYE* introduces a reuse service for the model truck, demonstrating R-strategies to extend the product's lifecycle. As depicted in Figure 3, each product is associated with its product AAS as well as all part AASs referenced in the Submodel *BillOfMaterial*. This allows an End-of-Life or circularity service provider to receive comprehensive product information in the form of a standardized AAS, including composition, materials, disassembly instructions or Product Carbon Footprint (PCF). All of this information constitutes the DPP. By following the approach of Jungbluth et al. (2023), vendor-independent data modeling is ensured for exchanging data assets with domain-specific knowledge. With standardized semantic and syntactical communication languages, as well as authentication and registration of participants in the dataspace, such an architecture for information exchange enables a data-sovereign, interoperable, and secure environment, leveraging the potential of the DPP for various participants along the product lifecycle.

Used products are delivered to _SKYE and can be identified by a QR code linked to the Product AAS. The first station is the manual disassembly process of the modular trucks with the help of the product AAS disassembly instruction Submodel, providing worker assistance (cf. Figure 3). Subsequently, an automated, visual quality assessment linked to an AI-based algorithm calculates a price based on the condition of the inspected part. The resulting quality rating is stored in the Submodel *QualityInformation* as the Property *QualityStatus* (integer $[0, 3]$ where 0 equals *brandnew*), forming the basis for automated marketplace offerings. In addition, the Property *LifecycleCount* (integer $[0, n]$ where 0 equals *first lifecycle*) is incremented, maintaining the current quality status within the parts AAS with the timestamp Property *InspectionDate*. The previous dataset of the quality properties is stored in the Submodel Element Collection *HistoricalData* to be able to track former lifecycles. The assessed part is then assigned a specific location in the reusable parts storage, ready for integration into a newly ordered truck configuration with used parts.

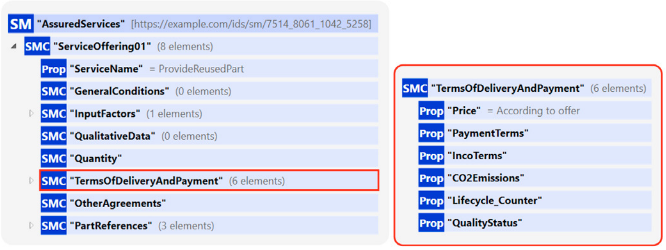
The DPP enables standardized and semantically annotated data exchange between independent stakeholders, facilitating decentralized decision-making for End-of-Life service providers. By analyzing the product AAS data,



- SM "CarbonFootprint" [https://industrialdigitaltwin.org/ids/sm/ProductCarbonFootprint]
  - SMC "ProductCarbonFootprint0" (6 elements)
    - Prop "PCFCalculationMethod" = GHG Protocol
    - Prop "PCFCO2eq" = 0.8 [kg]
    - Prop "PCFReferenceValueForCalculation" = piece
    - Prop "PCFQuantityOfMeasureForCalculation" = 1
    - Prop "PCFLiveCyclePhase" = A1-A3
    - SMC "PCFGoodsAddressHandover" (7 elements)
  - SMC "ProductCarbonFootprint1" (6 elements)
    - Prop "PCFCalculationMethod" = GHG Protocol
    - Prop "PCFCO2eq" = 0.04 [kg]
    - Prop "PCFReferenceValueForCalculation" = piece
    - Prop "PCFQuantityOfMeasureForCalculation" = 1
    - Prop "PCFLiveCyclePhase" = D - reuse
    - SMC "PCFGoodsAddressHandover" (7 elements)

Fig. 4. Product Carbon Footprints in Product AAS from Manufacturing and Reuse

it is possible to implement an R-strategy. This approach optimally reintegrates secondary parts or raw materials into the market, providing a competitive advantage due to a reduced CO_2 footprint compared to production including virgin materials. This advantage is explicitly disclosed in the Submodel *ProductCarbonFootprint* and the service offering, which directly fosters the development of corresponding business models by making the DPP accessible to participants in the dataspace. Figure 4 displays the PCF of a particular truck component, which comprises two sub-PCFs. The PCF of the manufacturing process is shown on the left-hand side, incorporating data from the lifecycle phases *raw material supply, cradle-to-gate and production*. After the first cycle, the reuse procedure was applied to that part, and the second PCF on the right-hand side was added. The decision to use a reused part results in a significantly lower PCF for the model truck compared to using a newly produced part. The reason is that only the second PCF is added to the part because of the reuse process, which then competes with the PCF of the initial manufacturing process of a newly manufactured component. The procedure of rating and reusing parts for model trucks and offering them as a service on the marketplace has been integrated into the demonstrator ecosystem. If customers configure a model truck, they now have the option to access offers from the reuse service provider and select used parts instead of newly produced ones, prioritizing the environmental impact of their order.



- SM "AssuredServices" [https://example.com/ids/sm/7514_8061_1042_5258]
  - SMC "ServiceOffering01" (8 elements)
    - Prop "ServiceName" = ProvideReusedPart
    - SMC "GeneralConditions" (0 elements)
    - SMC "InputFactors" (1 elements)
    - SMC "QualitativeData" (0 elements)
    - SMC "Quantity"
    - SMC "TermsOfDeliveryAndPayment" (6 elements)
    - SMC "OtherAgreements"
    - SMC "PartReferences" (3 elements)
- SMC "TermsOfDeliveryAndPayment" (6 elements)
  - Prop "Price" = According to offer
  - Prop "PaymentTerms"
  - Prop "IncoTerms"
  - Prop "CO2Emissions"
  - Prop "Lifecycle_Counter"
  - Prop "QualityStatus"

Fig. 5. AssuredServices Submodel in Factory AAS of Production Island _SKYE

The service offering is possible through the Factory AAS Submodel *AssuredServices* and the Eclipse Dataspace Connector[1] as a central communication part in dataspaces. According to the model in Figure 5, the service offering *ProvideReusedPart* is published on the marketplace for every reused part available. Besides the AAS ID of the specific component, terms of delivery and payment are also defined. Customers can compare components based on the offers with different information like prices, lifecycle status, quality and the PCF. The service offering corresponds to the component description of the respective product AAS as depicted in the *QualityInformation* Submodel from Figure 3. These automated service offerings for every individual part provide alternatives for customers during the product configuration phase. Instead of only having the option of newly manufactured parts, customers can now choose reused parts based on ecological and economical sustainability parameters.

Nevertheless, the discussed DPP approach has various technical and regulatory limits. First, the infrastructure's scalability concerning its capacity to effectively manage a vast volume of DPP instances and datasets and associated with this a complex change management. Second, the transferability of the DPP concept to diverse complex products, emphasizing the challenges associated with ensuring traceability across intricate supply chains. Furthermore, non-standardized terminology poses a considerable risk, potentially leading to ambiguities and inconsistencies, exacerbated by the adoption of company-specific solutions under political pressure. Last, the imperative for global standardization of DPPs, in line with emerging norms such as the AAS, is underscored, highlighting the necessity to mitigate the risk of counterfeit information within supply chains, ensuring authenticity and adherence to prescribed formats. Thus, influencing decision-making and ultimately trust in secondary materials.

5. CONCLUSION

This work demonstrates the implementation of a closed-loop supply chain network building on a mixed marketplace offering manufacturing services as well as reusable standard components. We leverage a dataspace infrastructure and the AAS to facilitate interoperable I4.0 language conform and trustworthy data exchange. The implementation also successfully shows the utilization of the DPP in the form of a product AAS to harness lifecycle-related information in end-of-use processes and the communication of the product state after a product's lifecycle between different stakeholders. It serves as a blueprint for the integration of other services into the platform along the product's lifecycle. This way, the full product circular value network can be incorporated.

The presented approach leaves the decision to buy a new or a used component to the buyer. In alignment with the DPP legislation, it trusts in informed consumer decisions for the more sustainable option if the sustainability KPIs like the PCF are made transparent. Further research needs to show if this free choice model will lead to a permanent change towards an increased circulation of secondary materials.

The general value of the platform naturally depends on the widespread adoption within a value network. This depends first and foremost on the subjective perception of trustworthiness. The most important pull factor is naturally the migration of key stakeholders in the value chain to a platform, where dependent actors would follow. Winning over the former depends hugely on the reliability of the data on the offered products. Thus, it remains to be proven that the adoption of data exchange via these platforms indeed leads to increased trust in the quality of secondary products, components and materials and therefore to a reduced preference for virgin materials. In

---

[1] https://github.com/eclipse-edc/Connector

particular, research conducted on the DPP could shed more light and provide hard data on this topic.

An important aspect of future research in this context also needs to be the research in the exchange and modeling of interpretable information about the product quality status beyond company borders. Particularly, a big gap exists in the transparency of the inspection process to inspire trust in the reliability of the data, especially in temporary supply chain relations.

ACKNOWLEDGEMENTS

This work is funded by the BMUV, project Green-AI Hub, grant number 57-E-2110.

REFERENCES

Adisorn, T., Tholen, L., and Götz, T. (2021). Towards a digital product passport fit for contributing to a circular economy. *Energies*, 14(8), 2289.

Battery Pass Konsortium (2023). Battery Passport Content Guidance. URL `https://thebatterypass.eu/assets/images/content-guidance/pdf/2023_Battery_Passport_Content_Guidance.pdf`.

Berg, H. and Wilts, H. (2019). Digital platforms as market places for the circular economy. Requirements and challenges. (27), 1–9.

Bergweiler, S., Hamm, S., Hermann, J., Plociennik, C., Ruskowski, M., and Wagner, A. (2022). Production level 4-der weg zur zukunftssicheren und verlässlichen produktion. *Whitepaper SF-5.1.*

de Jong, A.M. and Mellquist, A.C. (2021). The potential of plastic reuse for manufacturing: A case study into circular business models for an on-line marketplace. *Sustainability*, 13(4), 2007.

Diedrich, C., Belyaev, A., Bock, J., Grimm, S., Hermann, J., Klausmann, T., Köcher, A., Meixner, K., Peschke, J., Schleipen, M., et al. (2022). Information model for capabilities, skills & services.

European Commission (2020). A new Circular Economy Action Plan for a cleaner and more competitive Europe. URL `https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0098`. (Visited on 15.02.2024).

European Commission (2022). Proposal for Ecodesign for Sustainable Products Regulation. URL `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A0142%3AFIN`. (Visited on 15.02.2024).

Franklin, M., Halevy, A., and Maier, D. (2005). From Databases to Dataspaces: A New Abstraction for Information Management. *SIGMOD Rec.*, 34(4), 27–33. doi:10.1145/1107499.1107502. URL `https://doi.org/10.1145/1107499.1107502`.

Gaia-X European Association for Data and Cloud (2022). Gaia-X Architecture Document 22.10. URL `https://docs.gaia-x.eu/technical-committee/architecture-document/22.10`. (Visited on 15.02.2024).

Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S., and Chowdhury, T. (2022). Digital product passport: the ticket to achieving a climate neutral and circular European economy?

Jansen, M., Gerstenberger, B., Bitter-Krahe, J., Berg, H., Sebestyén, J., and Schneider, J. (2022). *Current approaches to the digital product passport for a circular economy*. Wuppertal Institute for Climate, Environment and Energy.

Jansen, M., Meisen, T., Plociennik, C., Berg, H., Pomp, A., and Windholz, W. (2023). Stop guessing in the dark: Identified requirements for digital product passport systems. *Systems*, 11(3), 123.

Jungbluth, S., Witton, A., Hermann, J., and Ruskowski, M. (2023). Architecture for Shared Production Leveraging Asset Administration Shell and Gaia-X. In *2023 IEEE 21st International Conference on Industrial Informatics (INDIN)*, 1–8. IEEE.

Koppelaar, R.H., Pamidi, S., Hajósi, E., Herreras, L., Leroy, P., Jung, H.Y., Concheso, A., Daniel, R., Francisco, F.B., Parrado, C., et al. (2023). A Digital Product Passport for Critical Raw Materials Reuse and Recycling. *Sustainability*, 15(2), 1405.

Łękawska-Andrinopoulou, L., Tsimiklis, G., Leick, S., Moreno Nicolás, M., and Amditis, A. (2021). Circular economy matchmaking framework for future marketplace deployment. *Sustainability*, 13(10), 5668.

Plattform Industrie 4.0 (2022). Details of the Asset Administration Shell - Part 1. URL `https://www.plattform-i40.de/IP/Redaktion/EN/Downloads/Publikation/Details_of_the_Asset_Administration_Shell_Part1_V3.pdf`.

Plociennik, C., Pourjafarian, M., Nazeri, A., Windholz, W., Knetsch, S., Rickert, J., Ciroth, A., do Carmo Precci Lopes, A., Hagedorn, T., Vogelgesang, M., Benner, W., Gassmann, A., Bergweiler, S., Ruskowski, M., Schebek, L., and Weidenkaff, A. (2022). Towards a Digital Lifecycle Passport for the Circular Economy. *Procedia CIRP*, 105, 122–127.

Potting, J., Hekkert, M.P., Worrell, E., Hanemaaijer, A., et al. (2017). Circular economy: measuring innovation in the product chain. *Planbureau voor de Leefomgeving*, (2544).

Pourjafarian, M., Plociennik, C., Rimaz, M.H., Stein, P., Vogelgesang, M., Li, C., Knetsch, S., Bergweiler, S., and Ruskowski, M. (2023). A Multi-Stakeholder Digital Product Passport Based on the Asset Administration Shell. In *2023 IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA)*, 1–8. IEEE.

Rilling, L., Schneider, A., and Castelli, N. (2023). Towards Data Spaces for circular economy and green business value networks.

Simon, M., Jungbluth, S., Farrukh, A., Volkmann, M., Hermann, J., and Ruskowski, M. (2023). Implementation of Asset Administration Shells in a Shared Production Scenario with Gaia-X. In *2023 IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA)*, 1–8. IEEE.

Volkmann, M. (2024). *Modellierung von Dienstleistungen, Capabilities und Skills zur Einbindung von Unternehmen in eine marktplatzbasierte Fertigung.* Ph.D. thesis, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau.

Walden, J., Steinbrecher, A., and Marinkovic, M. (2021). Digital product passports as enabler of the circular economy. *Chemie Ingenieur Technik*, 93(11), 1717–1727.