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Digital Product Passport enabled Quality Assessment in Dynamic Circular Supply Chain Networks

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Abstract

One of the big challenges in circular economy practice is the management of the forward and reverse supply chain simultaneously. Specifically, the varying quality state of secondary products, components and materials makes it difficult to manage the variety of paths and involved stakeholders towards the reintroduction of secondary materials into their next use phase. B2B marketplaces enable the simple integration of the participating stakeholders along a product's lifecycle into a common value chain management and enable the formation of dynamic, needs-oriented supply chains. Traceability tools, like the emerging Digital Product Passport (DPP), ensure a continuous information flow among all lifecycle actors. This paper shows how the DPP can be leveraged to facilitate the processes at the end of the product life. Specifically, it presents an approach to integrate Quality Assessment into the reverse supply chain. It proposes to utilize a DPP based on the Asset Administration Shell to establish a common understanding of an object's quality state between stakeholders. The availability of reliable, standardized quality information has the potential to improve supplier-buyer matchmaking on B2B marketplaces and to increase trust. The concept is demonstrated on a usecase in a dynamic manufacturing environment.

Keywords: Circular Economy; Digital Product Passport; Asset Administration Shell; Automated Visual Inspection

1. Introduction

The establishment of a circular economy (CE) is one of the pillars of the European Green Deal. It defines the goal for Europe to become the first continent with net-zero emissions of greenhouse gases by 2050 [1]. This is further specified in the Ecodesign for Sustainable Products Regulation [2] under the Circular Economy Action Plan [3]. The regulation defines the Digital Product Passport (DPP) as a key measure to establish a general information exchange framework on product data along its complete lifecycle. As such, the DPP is supposed to remove information asymmetries among the stakeholders of the product's lifecycle.

The concept of creating circular lifecycles for products, components, and materials is described by the R-strategies [4]. Key R-strategies are illustrated in Figure 1. These strategies outline the processes involved in reprocessing products that have reached the end of their use phase. By incorporating these used products or components as secondary materials into the lifecycles of new products, circular supply chains are established [5].

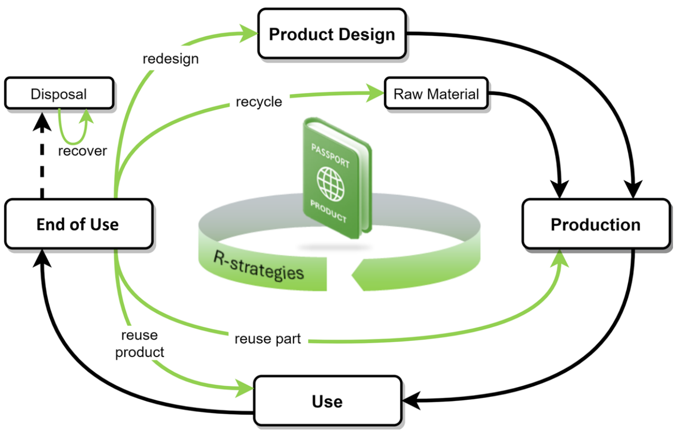

Fig. 1. The Digital Product Passport as a lifecycle overarching data node

The management of a circular supply chain network, in which secondary material streams need to be reintegrated at various stages into the production process, however, remains a complex challenge. Digital marketplaces can play a key role in the establishment of dynamic business relationships. In a circular supply chain, this is vital in order to dynamically involve various stakeholders to account for the fluctuating quality and amount of the different secondary material streams [6].

On the opposite side stands an increasing demand for individualized products, and to extend and intensify their use phase. This also fosters strategies like customizing the product design for greater attachment of the user and increased trust in and reliability of the product in varying environments [7].

Enabling the mass customization of products is one of the core targets of Industry 4.0 which focuses on highly flexible automation [8]. Cloud manufacturing is an extension of this concept beyond company boundaries. Shared Production brings the concepts of cloud manufacturing for mass customization and digital marketplaces together [9]. With the advent of the CE, the Shared Production must be able to accomodate secondary materials, and these secondary materials need to be "attractive" enough to be able to compete with virgin materials. This can be facilitated by digital B2B marketplaces.

Digital B2B marketplaces play a crucial role in organizing the supplier-buyer matchmaking for secondary materials and products in circular supply chains. However, information deficits on the condition and the quality of secondary goods are a central issue for lacking trust in supplier-buyer relationships [6]. A challenge here is the inherent information asymmetry between supplier and buyer, where the buyer has to trust the information on the product provided by the supplier [10], and often this information is poor in quality and/or quantity. This may be due to an unwillingness or inability to disclose information (*performance uncertainty*) or an inability to properly analyse the condition of the offered goods (*description uncertainty*) on the side of the supplier [11].

We have addressed the issue of *performance uncertainty* in a previous publication [12]. There, we proposed to leverage the concept of dataspaces for opening a trusted and secure channel to share sensitive data among the different stakeholders. The information exchange itself is then achieved via a Digital Product Passport (DPP) based on the Asset Administration Shell (AAS), an interoperable information model. While this approach has the potential to reduce *performance uncertainty*, it is but a first step. This paper builds on our prior work and addresses the problem of *description uncertainty* – which constitutes the second step to establish a trusted supplier-buyer relationship in circular supply chain networks. We achieve this by leveraging the established dataspace and DPP infrastructure for end-of-life processes of used products. Specifically, we show how it can be used to both assess and communicate quality information related to secondary materials and products. This is exemplified in a usecase in the *SmartFactory*^{KL}.

This paper is structured as follows: Section 2 discusses related work. Section 3 describes the concept. Section 4 presents its implementation in the usecase. Section 6 concludes the paper and discusses future work.

2. Related Work

2.1. Circular Supply Chain Management

Several publications have dealt with the challenge of how to close the resource and information loop in supply chains to make them circular. Kurilova-Palisaitiene et al. examine which information flows are present in the CE from a remanufacturing perspective [13]. They find that significant information losses occur, especially from product development towards remanufacturing and vice versa. Here, information flows must be improved. Zhang and Seuring look specifically into Circular Supply Chain Management usecases related to the DPP [14]. They find that different DPP concepts are being established to solve different tasks in the CE, but the DPP has not been employed to facilitate quality assessment at the end of the product life.

2.2. Asset Administration Shell as Digital Product Passport

The DPP is devised to serve as an information repository about the product and also as the interface between the stakeholders of the product lifecycle to exchange data. As such, the DPP contains e.g. technical product descriptions (e.g. bill of materials, declaration of hazards) as well as documentation of the individual product lifecycle (e.g. individual CO2 footprint, repair logs) [15].

The development of the DPP is closely related to the concept of the digital twin, which represents an adaptive synchronized digital model of the physical object [16]. The Asset Administration Shell (AAS) specifies a technology neutral metamodel for the implementation of digital twins [17] and has been used to describe products as well as production equipment in the context of flexible manufacturing [18]. Thus, the AAS is often propagated as an obvious fit for the implementation of a DPP [19] and first research already explores this application [20].

Nevertheless, for automatic interpretation and interoperability, the approach relies decisively on the standardization of information models and the semantic definition of described data values in domain ontologies [20]. With the latter, the connection of multiple AASs in the semantic domain for querying and validation can be enabled [21]. However, there is currently still a lack of standardized and interconnected vocabularies and submodel templates describing the condition of a product throughout its lifecycle.

2.3. Supplier-Buyer Matchmaking for Circular Economy

The utilization of online marketplaces in the creation of flexible supply chains in a circular economy has already been emphasized by Berg et al. [6]. A central aspect to enabling a dynamic relationship between supplier and buyer is the matchmaking between these two actors. Several approaches have been pursued over the years.

The authors in [22] sketch out a mixed marketplace with virgin and secondary materials. Considered criteria for the matchmaking are compliance with circular economy principles, material flows, and greenhouse gas emissions. Matchmaking for a

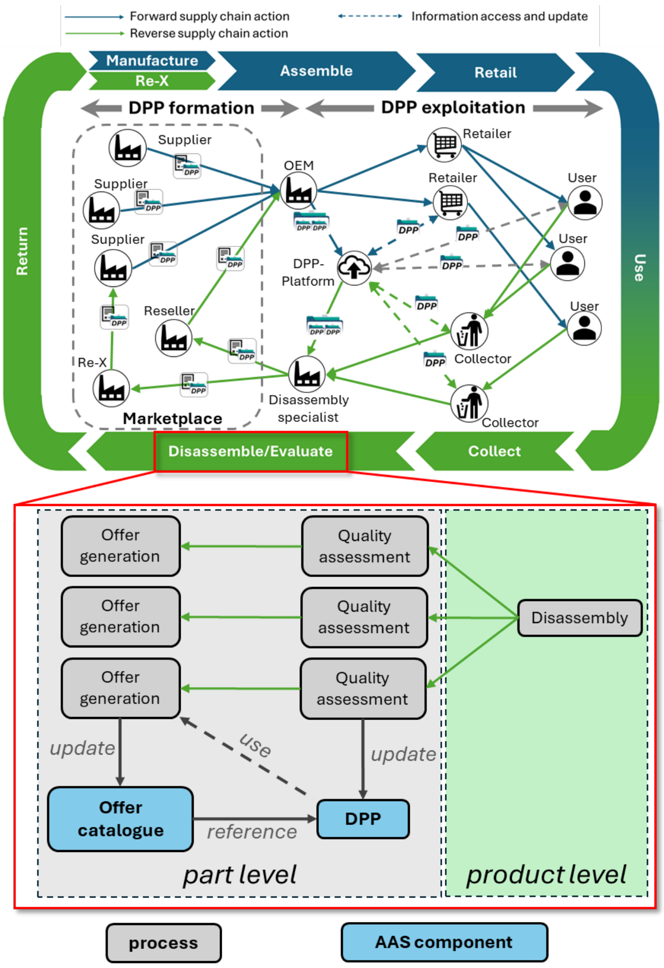

Fig. 2. Circular supply chain (top) and zoom-in on the end-of-life (bottom).

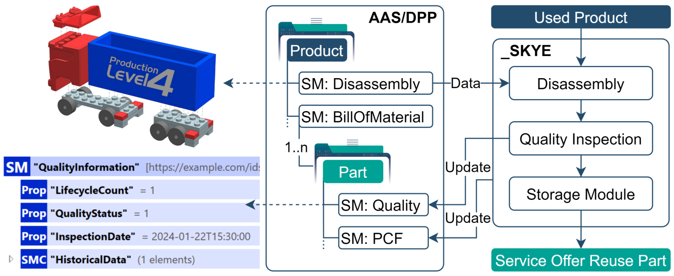

Fig. 3. Procedure of reuse service at the production island _SKYE

circular economy in the construction industry was investigated in [23]. This approach is tailored towards the French regulatory environment and leverages the PEMD audit [24] results of materials from demolition sites for the matching. The auctioning approach is pursued in [25] and [26]. Both approaches describe fully automated flexible matching and contract negotiation via bidding protocols of autonomous agents. Bodin et al. specifically describe a matchmaking based on a composite suitability score calculated from factors like the marginal reuse rate [25].

3. Concept

As mentioned in the introduction, in the CE, we want to minimize waste and close the loop such that products or parts of products can last for more than one life cycle. Hence, actors in different life cycle phases must communicate about the product, but this is not easy to achieve. In our previous publications [27, 20, 28], we have shown how the DPP can be employed as a connection (information-wise) between the different phases of one life cycle to facilitate communication among the stakeholders associated with each life cycle phase. Here, we show how the DPP can be employed to tie different "lives" of a product or component together and facilitate its reuse, refurbishment, or remanufacturing.

Hence, we zoom in on the interface between the two life cycles. Figure 2 depicts the circular supply chain with the involved life cycle stages and ecosystem of stakeholders (top) and the integration of the end-of-life process into this life cycle (bottom).

For the smooth transition of the product/component into its new life cycle, it is important that both the end-of-life actor of the first life cycle and the beginning-of-life actor of the second life cycle communicate about the quality and associated risks of the used product. To capture this quality information and thus facilitate the communication, we employ a DPP based on the AAS.

In detail, the process is as follows: The used product is collected and brought to *Disassembly*. Once it has been disassembled, the physical components can be stored for the next step, while an AAS submodel for each component is generated if it does not already exist. This is the information base for the next steps. The next step is the *Condition examination* where the state the components are in after their use is determined. This Condition examination step has three substeps:

1. *Damage detection*: Here, the damages to the components are determined, e.g., by optical means. Then the damages are recorded.
2. *Risk assessment*: This takes as input the damages recorded in the damage detection and determines an associated risk score for each damage, which is then recorded. The risks can be related to the component itself, e.g., the risk of failure in the future, or to its usage. An example here is a safety risk for a future user, for instance because of sharp edges due to a broken off part.
3. *Quality rating*: The Quality rating computes the quality status of the component based on the risk score, and records it in the *QualityInformation* submodel of the DPP. Additional information can be recorded as well, such as the count of the lifecycles the component has already seen.

After the Condition examination comes the last step in the "old" lifecycle, the *Sale* step. Now the component is offered on a digital marketplace, where manufacturers that include used components in their products buy their supplies. The basis for this step is the DPP and, more specifically, the QualityInformation submodel. Based on the information in the QualityInformation submodel, the seller can determine a suitable price for the used

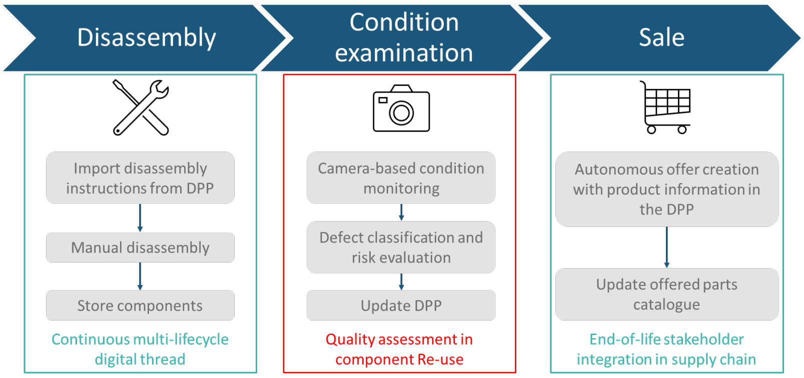

Fig. 4. The different steps in the end of life of the model truck.

component and the buyer can determine whether the components matches his requirements and the price is reasonable.

Of course, it must be ensured that the involved actors (buyer and seller) can not only *share* the quality information, but also *understand* each other. This is a big challenge since different actors must agree on a common terminology, like for example which quality classes are useful. Different actors, in this case, ultimately means not only different companies, but also different industries. The details of this are beyond the scope of this paper, but we present some options how this can be achieved in the following.

One way to achieve this is to employ ontologies that define the concepts and relationships relevant for the DPP. Work on such DPP ontologies is still in its infancy, but there are first steps in that direction [29, 30]. Once the DPP has gained a critical mass of users, standardization is also an option. Standardization has the advantage that concepts are clearly defined and ambiguities are avoided. However, standardization is a community effort. This means it takes time since the relevant stakeholders must agree on a common standard. Therefore, standards for the DPP are still rare. For the AAS, standardization is brought forward by the Industrial Digital Twin Association (IDTA). The IDTA standardizes AAS submodels so everyone can use them. Our proposal for a QualityInformation submodel is a first step in the direction of such a standard.

4. Implementation

In this section, we exemplify the concept introduced above on a usecase in a dynamic manufacturing environment. We implemented the usecase on the vendor-independent demonstration and research platform of *SmartFactory*^{KL} which includes five production islands, 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. 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 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.

Used products are delivered to _SKYE and can be identified by a QR code linked to the product AAS. Now the steps *Disassembly*, *Condition examination* and *Sale* are performed as introduced in Section 3. These are depicted in Figure 4.

4.1. Disassembly

In the *Disassembly* step, we first look up the disassembly instructions in the AAS-based DPP of the model truck. Then, a worker performs a manual disassembly of the truck into its components. The individual components are then put on hold for further processing. In the next step, this DPP will be used to accomodate the quality information related to the component.

4.2. Condition examination

The next step is the Condition examination. It is more comprehensive than the other two steps and can be divided into the substeps shown in Figure 5: *Damage detection*, *Risk assessment*, and *Quality rating*.

Damage detection. Here, damages from the usage phase of the product are detected. For this, we employ an AI-based damage detector that can detect scratches, stickers, and similar damages. To be more precise, A YOLO v5 neural network object detector is used. It gets images of all sides of the product as an input and produces a damage report as an output.

Risk assessment. This substep gets the damage report generated in the previous substep as an input. It then calculates a risk score for each damage. Methodologically, a knowledge graph is employed to generate these risk scores. It is depicted in Figure 6. The risk scores of the individual damages are then summed up to a cumulated risk score.

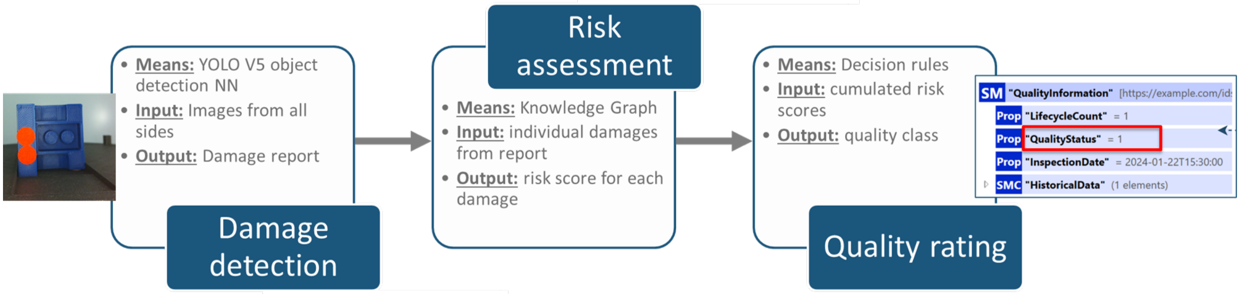

Fig. 5. The substeps *Damage detection*, *Risk assessment*, and *Quality rating*, which are part of the step *Condition examination*.

Quality rating. Here, the cumulated risk score is taken from the previous substep and, with the help of decision rules, is computed into a quality class which can be a number between 0 and 3. This quality class is stored in the DPP. To be more precise, the Property *QualityStatus* (integer [0, 3] where 0 equals *brand-new*) in the AAS Submodel *QualityInformation* is updated accordingly (see Figure 5). This is important since it enables communication with potential buyers in the next step.

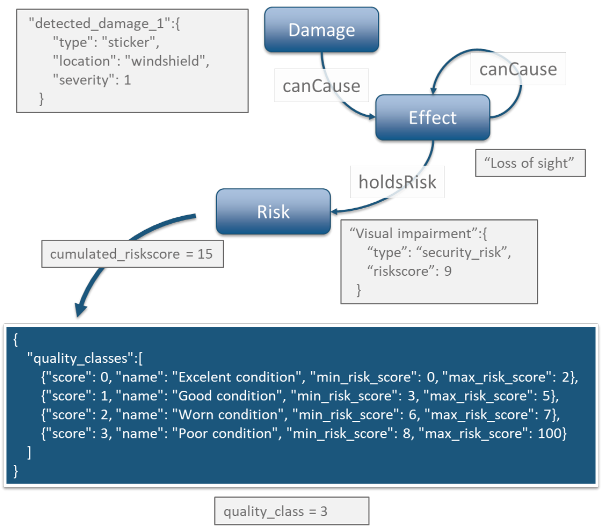

Fig. 6. A zoom-in on the *Risk assessment* substep that employs a knowledge graph.

4.3. Sale

Here, an offer for potential buyers of the component is generated. It takes the quality class from the previous step as an input and calculates a price for the used component. This price is then recorded in the DPP. Afterwards, it is used alongside other DPP information to advertise the used component in a catalogue of used components that other production islands in the *SmartFactory*$^{\mathrm{KL}}$ can access. When ordering a new model truck, customers can now choose whether they want to include used components in their ordered product and, if yes, which ones. They are also informed about the CO2 equivalent that is saved compared to a model truck consisting entirely of new components. Hence, the benefits of R-strategies can be experienced via the _SKYE demonstrator.

5. Discussion

In our usecase, we have defined 4 quality classes to capture the state of the used product. This solution is rather coarse and static. It constitutes but a first approach to communicate the quality of the product with the ultimate goal of reselling the component and integrating it into a new product. To make this process more flexible and interactive, a bidding process can be envisioned. It could comprise a *browsing phase*, where the buyer can evaluate and filter different offers fitting to his need, a *negotiating phase* where the requirements of the buyer and the quality of the object can be set in relation and balanced against each other by the actors, and a *bidding phase*, where the buyer places a bid with the supplier, who can ideally decide between different offers.

The approach described in this paper adds to the collection of available usecases related to the DPP and circular supply chain management. To the best of our knowledge, the DPP has not been used to facilitate supplier-buyer matchmaking and to communicate quality information on a B2B platform related to the CE [14]. Hence, our approach can also be viewed as a proposal for a new application of the DPP. As such, it contributes to the body of research on supply chain collaboration, a research need identified by Zhang and Seuring [14].

6. Conclusion and Future Work

In this paper, we have presented a concept for an integration of Quality Assessment into the reverse supply chain in order to facilitate the use of R-strategies. The goal is to close the loop of products and components within a Circular Economy. Our approach emphasizes the need for a common understanding of quality criteria between an end-of-life actor and a potential buyer of used products and components. We have also shown ways how to achieve this common understanding. A key cornerstone here is the Digital Product Passport based on the Asset Administration Shell. Our approach facilitates supplier-buyer matchmaking on B2B marketplaces for secondary products and materials and has the potential to increase trust among the stakeholders. This, in turn, can decrease *description uncertainty*. We demonstrated our concept in a usecase implementation in the *SmartFactory*$^{\mathrm{KL}}$.

A future research avenue is to include further indicators for environmental impact (e.g., abiotic depletion potential) in the

DPP – at the moment, we have only the Product Carbon Footprint. These indicators could be calculated by life cycle assessments (LCA) [31] and would allow the buyer a more informed choice of products from the marketplace. First concepts of a product-specific LCA method based on the DPP exist [28], but they are still in their infancy.

Acknowledgements

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