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Towards a Digital Lifecycle Passport for the Circular Economy

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Abstract

The Circular Economy approach aims to close the loop of materials and to reduce waste. However, relevant product data for the optimization and management of circular approaches are often missing. Stakeholders typically lack key information: Recyclers do not know which materials/compounds to expect, producers do not know enough about the recyclability of their products, and customers do not have enough information about the environmental impact of their purchases. As a solution, this paper proposes a Digital Lifecycle Passport (DLCP) that can be written and read by various stakeholders along the full product lifecycle. Based on Plattform Industrie 4.0's Asset Administration Shell, the DLCP is readable for both humans and machines. A cloud-based app (SaaS) enables all stakeholders to create and manage DLCPs. As a use case, it is demonstrated how the DLCP can improve the sorting process of electronic waste.

Keywords: circular economy; Digital Lifecycle Passport; Digital Product Passport; Asset Administration Shell

1. Introduction and Motivation

Anthropogenic environmental impacts are driven by the way our societies make, consume, and dispose of products. During the lifecycle of all products, humanity consumes non-renewable and renewable materials and energy, and releases emissions, which impact air, water and soil, and ultimately earth's support systems [1]. As a result, it is widely accepted that humanity must decrease the detrimental environmental impact of industrial processes. This is in line with the Circular Economy (CE) paradigm, which tries to reduce waste by keeping materials in the loop for as long as possible by reusing, repairing, refurbishing, and recycling products or their components [2]. The EU strives to promote CE approaches with the European Green Deal [3] and the Circular Economy Action Plan [4]. Consequently, CE approaches have been the subject of research and have progressed greatly in recent years. End-of-life products are increasingly being collected and remanufactured or recycled. Product-related data, however – such as material flows, and how products should be disassembled, or whether they contain hazardous materials – are rarely exchanged between stakeholders. Manufacturing companies, on the other hand, get little feedback on how their products are being processed at their end of life – whether they are recycled, and which problems occur during recycling. Users lack information about which products are produced with little environmental impact, and whether and to what extent they are recyclable.

To improve the efficiency of the circularity approach, this paper proposes a product-agnostic data structure called **Digital Lifecycle Passport** (**DLCP**, see Figure 1). It is hosted on a cloud platform and can be accessed via a progressive web app by producers, users, recyclers, and other stakeholders along the product's lifecycle. The DLCP aims to facilitate the communication among the stakeholders along the lifecycle: During production, producers can record which materials and additives the product contains, how it was assembled etc. This information can benefit the recyclers later in the lifecycle, since it enables

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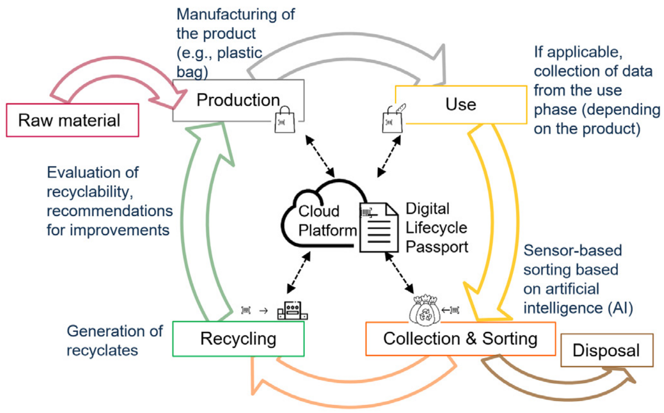

Fig. 1. The DLCP stores information along the product lifecycle.

improved sorting decisions. Recyclers in turn can record experiences from the recycling process, which then enables producers to improve their product design. In addition, robust lifecycle assessments can be carried out based on this data. Thus, the proposed DLCP enables the optimization of the lifecycle of a product, reducing the demand on natural resources and contributing to the circular economy.

To foster adoption by various industries, the DLCP relies on an information model that is easy to extend and widely supported: The DLCP is based on Plattform Industrie 4.0's Asset Administration Shell (AAS) [5], which is jointly being developed by a multitude of organizations from industry, research, and industrial associations [6]. The DLCP can be written and read by both humans and machines. This is key for smooth communication along the lifecycle and for seamless machine connectivity. As a use case, it is demonstrated how the sorting of electronic waste can be improved by combining machine-learning based object detection and information from the DLCP.

This paper is structured as follows: Section 2 discusses related work, Section 3 introduces the concept and implementation of the DLCP, Section 4 describes the cloud-based app, Section 5 introduces the use case, Section 6 discusses open issues and Section 7 concludes the paper.

2. Related Work

2.1. Existing approaches to describe product-related data

There are several initiatives and approaches to collect and share data along the product lifecycle. One example is the **Digital Product Passport**, a concept envisioned by the EU [4] and the German environmental ministry (BMU) [7]. The Digital Product Passport is a data set that contains information on the components, materials, and chemical substances, repairability, spare parts or proper disposal for a product. It is being extensively discussed in [8], and the authors propose the Asset Administration Shell (AAS) as a possible basis for implementing the Digital Product Passport. According to [9], manufacturers are the most important source of information for the DPP. Therefore, it is important that manufacturers perceive the approach as a benefit, not a burden.

Another approach that is related to a specific product category is the **Battery Passport** [10]. Its goal is to ensure sustainability and safety of all batteries in the EU. By 2026, it will be mandatory to accompany certain batteries with a data structure that is accessible online and linked to the physical battery via a QR code. It will contain information about e.g. capacity, lifetime, and presence of hazardous substances. The details of this data structure and its storage are yet to be defined. A similar approach is the **Battery Identity Global Passport** [11]. Other material-agnostic initiatives include the **Materials Passport** [12], the **Product Circularity Data Sheet** [13], and the **Resources Passport** [14], which is co-developed with a platform that matches waste and secondary material offerings with demand. These approaches are, however, either on the conceptual level, lack an implementation that is both human and machine readable, or are not open to contributions from all stakeholders in the lifecycle.

2.2. Asset Administration Shell

A core aspect of Industrie 4.0 is flexible and reconfigurable production in order to cope with rapid changes and to enable small batch sizes. The Asset Administration Shell (AAS), promoted by the German-led Industrie 4.0 initiative, plays a major role in achieving the Industrie 4.0 goals, since it enables data sharing between value chain partners, standardizing data security, and providing technology-neutral semantic standards [5]. The reference architecture model Industrie 4.0 (RAMI 4.0) [15] specifies how an asset should be represented in the information world. An asset can be any manufacturing object of value, physical or non-physical [5, 16]. An asset combined with its AAS is defined as an I4.0 component. It serves as an abstraction layer that unifies access to basic and context information about an asset. The structure of the AAS information model comprises a list of submodels in which various characteristics of an asset, such as its specific functionalities and technical aspects, are modeled and stored (see Figure 2).

The AAS is increasingly being used for ecologically related applications. Assadi et al. [17] carried out an environmental impact analysis: They collected data about energy consumption and emissions during a production process using AAS and were able to relate them to the corresponding products and equipment. Schmidt and Adler [18] introduced a standardized approach for modelling lifecycle information. They established a digital lifetime file (German: digitale Lebenslaufakte) based on the AAS metamodel as well as industrial standards such as DIN 77005-1 [19]. However, they focused on information management for the installation phase and the implementation of the concept was out of their scope.

3. Digital Lifecycle Passport

Currently, there is a lack of uniform and consistent structures for information related to products and their lifecycle. This can lead to individual problems relating to the exchange of information in the lifecycle of products. One solution is to introduce a standardized common model to represent the lifecycle information of products. By providing standardized information, it can be distributed and transferred from one company to another not only in a meaningful (semantics) but also structured (syntax) manner. This ensures both syntactic and semantic interoperability [20] of the DLCP.

3.1. Definition of the Digital Lifecycle Passport

The DLCP is both an implementation and an extension of the concept of Digital Product Passport defined by the German environmental ministry (BMU) [7]. It is a dynamic and digital node for the exchange of information among all actors involved in the lifecycle of a product. The DLCP goes beyond the idea of the Digital Product Passport in the sense that stakeholders along the lifecycle can read and write content. It is intended to be accessible and user-friendly for all actors. Based on standardized data, it quantifies and reports the environmental impacts and natural resource use considering the entire lifecycle of a product.

In this work, a product is considered an asset since it is a valuable object in the manufacturing industry. Therefore, an AAS is defined for each product asset. The Industrie 4.0 Asset Administration Shell meta-model is used to model the DLCP. By having an AAS for a product we can model different aspects of a product in respective sets of information in so-called “submodels” in AAS.

Within the scope of this work, all information that is defined in the Digital Product Passport is considered as relevant lifecycle information (see Section 2.1). Since the Digital Product Passport itself is work in progress, further information will likely be contributed in the future. The DLCP approach makes this possible because the AAS is easy to extend.

3.2. Modelling the Digital Lifecycle Passport in the Asset Administration Shell

In principle, the AAS is capable of representing a wide range of product-related data. This work focuses on lifecycle information. The AAS’s easy extendibility, however, allows stakeholders throughout the lifecycle to store additonal information that is not directly related to the lifecycle, such as manuals for usage or energy consumption data, which makes the AAS a viable and lasting solution for fulfilling diverse information needs. Information is organized in submodels. For this work, a set of submodels (see Figure 2) has been defined for a product that represents different categories of its related information.

Some of the submodels and their properties are defined and created based on industrial standards such as ECLASS standard [21], and DIN 77005-1 standard [19]. ECLASS is a cross-industry standard that provides master data for the classification and unambiguous description of products and services [21]. DIN 77005-1 standard [19] is provided by the German Institute for Standardization (DIN) and identifies the lifecycle record of technical objects. This brings the benefit of providing semantic

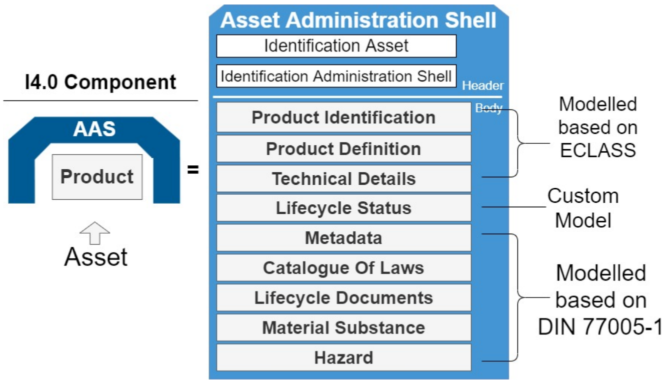

Fig. 2. Structure of the Digital Lifecycle Passport based on Asset Administration Shell (AAS).

interoperability, and to ensure that information is exchangeable in a meaningful manner. Submodels can contain both static and dynamic information. The *Product Identification* submodel, for instance, is defined based on the ECLASS standard [21], which holds all the static information that identifies a product, e.g. a standardized and unique identifer or information about the manufacturer.

Another example of the static information is the legal catalogue that is modeled in a submodel named “Catalogue Of Laws” which is defined based on the DIN 77005-1 standard. This submodel specifies the legal framework for the technical installation of a product, as well as its operation and provisions relating to different parts of the product.

The DIN 77005-1 standard also defines dynamic lifecycle information, and has been modeled as “Lifecycle Status” submodel for this work. This submodel contains the main attributes of lifecycle phases, such as title, start date of phase, end date of phase, its possible subphases, etc.

Some of the dynamic information is application-specific. For instance, in the e-waste sorting use case described in Section 5, object categories and sorting information are provided by a machine learning algorithm and by a sorting decision algorithm. This information can be modeled and stored in an individual submodel. This is future work.

4. Cloud-based App

DLCPs are stored in a hybrid cloud according to the National Institute of Standards and Technology (NIST) [22] and can be created, retrieved and maintained via a web app (see Figure 6). The system architecture is shown in Figure 3.

The cloud infrastructure consists of a community cloud and a public cloud. It allows all relevant actors to interact with DLCPs based on a sophisticated role concept. Different roles such as DLCP architect, DLCP provider, DLCP analyst, Cloud Customer, and Cloud Visitor enable fine granular access rights to be assigned.

As mentioned above, the DLCP based on the asset administration shell is composed of a set of submodels. Different stakeholders can be owners of submodels of a DLCP. Each stakeholder can either grant specific access rights to members in

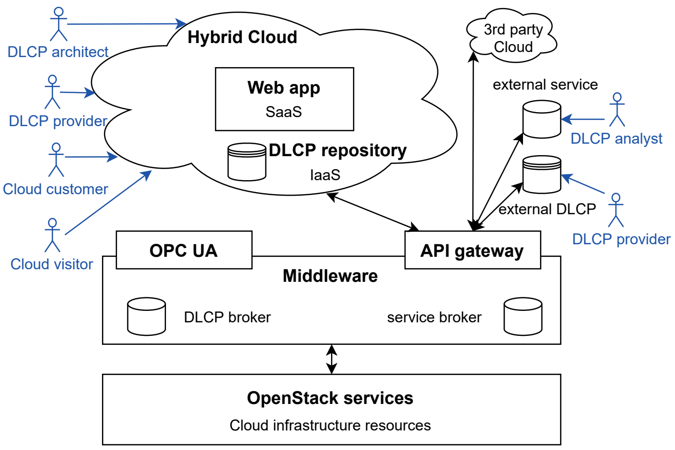

Fig. 3. Architecture of the hybrid cloud.

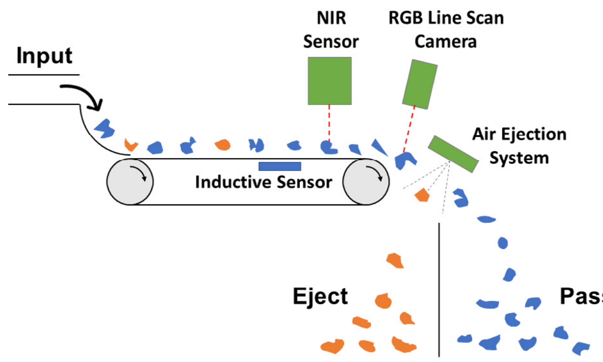

Fig. 4. Representation of the multi-sensor sorting system for the use case.

the community cloud or make their information available to the general public as part of the public cloud.

DLCPs are stored in AASX format, which is the official format for providing an asset administration shell as a file [23]. For reading and writing AASX files, a toolkit called AASX server is available. An external AASX server has been integrated into the cloud platform via a REST API. The web app provides a user interface to the AASX server that hides the complexity of the AASX syntax from users. This allows users to easily create and manage DLCPs.

Communication between the hybrid cloud and the cloud infrastructure is handled by a middleware. A DLCP broker allows the inclusion of external DLCPs by means of a registry. In addition, external analysis and optimization services from third-party providers can be made available for DLCPs, using REST and a service broker. [1] Users can interact with these third-party services via the web app. Examples include a lifecycle assessment service (openLCA [25]) and the sorting decision service implemented for the use case, which is described in the next section. For the future, further interfaces in the middleware for connecting external clouds as well as machines are planned.

5. Use Case

For this work, a first use case has been implemented on a sorting machine to demonstrate that the DLCP can improve waste sorting processes: The DLCP is combined with AI based object detection for the sorting of waste from electrical and electronic equipment (WEEE) with a multi-sensor sorter. Combining these two types of information enables individual sorting decisions that would not be possible without the DLCP.

Figure 4 shows a representation of the sorting system used for each of the sorting steps. The multi-sensor sorting unit is equipped with three sensors to detect object properties. The RGB line scan cameras detect colors in the visible spectrum of light, while a hyperspectral near-infrared (NIR) camera is able to distinguish material characteristics of polymers such as plastics, paper or wood. An inductive sensor is used to detect metals and other conductive materials. For this first implementation, images from the RGB camera are fed into a neural network-based object detector (SSD512 [26]) that recognizes the type of each device being sorted. In the future, NIR and metal detector data will be included.

The sorting use case is divided into two steps: As shown in Figure 5, end-of-life products specified by the German regulation ElektroG collection group 5 [27] (WEEE), such as routers, network switches, telephones, mobile phones and navigation devices are fed into **sorting step 1**, which separates hazardous from non-hazardous materials. Devices that contain problematic or hazardous substances or components need to be pretreated prior to further processing. They are therefore ejected and fed into a subsequent more specific sorting. In this use case, the ejected devices are display devices, such as smartphones or GPS navigation devices. These are typically meant for mobile use and are likely to contain batteries that by German law (ElektroG) need to be removed before further treatment. The unproblematic rest of the WEEE stream passes the system and is routed towards a manual disassembly or automatic comminution process. Sorting works as follows: Images from the sorting system are fed into the neural network that detects the type of the device. The recognized device category is used to query the cloud platform for the respective DLCP. The information whether this device is likely to contain a battery is extracted and sent back to the sorter, which can then sort out these devices.

Sorting step 2 aims at separating high-value objects, such as smartphones, from the stream of devices with batteries. The high-value objects are ejected from the stream to be treated by a semi-automatic process for battery removal, called Electro-Hydraulic Fragmentation (EHF). The remaining stream, i.e. the rest of the display devices, is fed into a manual removal of the battery before a manual or automatic downstream treatment. The separated components and materials of the different streams would then be sorted into marketable fractions. In this step, after the device type has been detected by the neural network, the DLCP provides information about the concentration

[1] RM-SA [24] distinguishes between service and I4.0 service. Since it can be assumed that not all stakeholders from the sustainability field know how to provide administration shells for I4.0 services, the possbility of connecting services via the broker has been added.

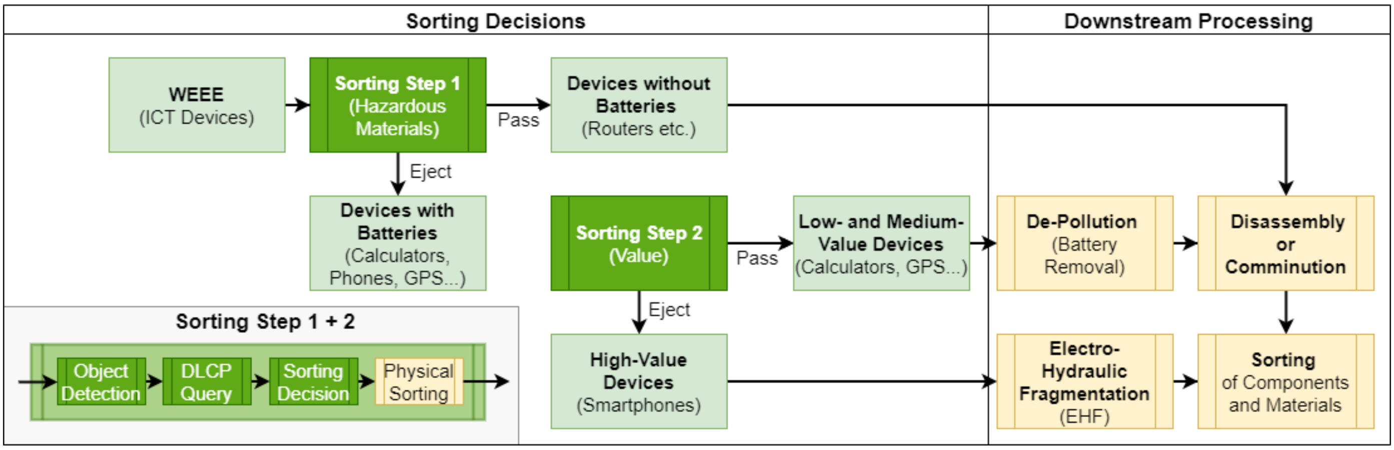

Fig. 5. Overview of the sorting process in the use case.

of gold and other valuable materials within the object. According to this information, a sorting decision is made: high-value devices (those that contain a significant amount of gold) can be ejected, and low- and medium-value devices remain in their stream. Preliminary results are depicted in Figure 6. The physical sorting on the sorting machine according to this information is work in progress.

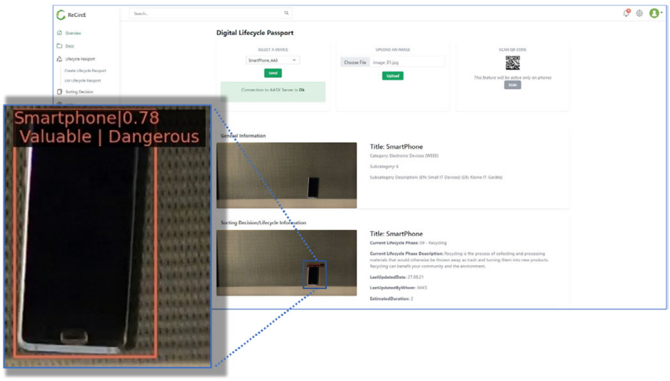

Fig. 6. Results of the sorting process in the web app (enlarged for readability) – device type, confidence score, value and hazardousness are reported.

6. Open Issues

Several open issues remain. Two are discussed briefly here.

6.1. Linking the DLCP to the physical object

There are several ways to link the DLCP to its corresponding physical object. For the first implementation in the use case, the physical object is identified via machine learning based object detection. Once the object category has been identified by the object detection, its corresponding DLCP can be retrieved. This approach, however, is only feasible for a comparatively small number of object categories. If many different objects must be identified, marker-based solutions are suited better, such as optical markers (e.g., QR codes), RFID [28], chemical markers, or watermark-based approaches [29]. There is no solution that fits all industries or products. Which identification technology is best suited depends on the requirements of the application.

6.2. One DLCP per product category vs. one DLCP for each individual product

For the first implementation in the use case, a DLCP has been created for each product category. This may, in practice, only be realistic for simple, short-lived products, such as plastic packaging. In contrast, providing a DLCP for individual (complex) products enables to record the product's history, e.g. its production date or the date of its last maintenance. Which approach is feasible for which kind of product is subject to further research.

7. Final Considerations and Outlook

This paper introduced the concept and implementation of a Digital Lifecycle Passport based on the Asset Administration Shell along with its management via a cloud-based app. It has been shown that the DLCP and machine learning based object detection enable fine-grained sorting decisions in an e-waste sorting use case: E-waste objects in a sorting system are identified via object detection, and based on this, each object's DLCP can be retrieved. The DLCP, in turn, contains information whether the object contains hazardous substances and how much gold it contains. This allows to automatically sort out dangerous and high-value objects, and hence reduces the need for manual sorting. Therefore, the DLCP in conjunction with object detection has the potential to automate sorting processes.

This, however, is just one of many possible applications of the DLCP and the cloud platform. One could, for instance, automatically generate lifecycle assessments (LCAs) based on the data collected via the DLCP. To achieve this, one could implement an LCA service for the cloud platform to enable automated environmental assessment of products via simplified or streamlined LCA. The standardized collection of information can be in alignment with and should be used for methods calculating environmental impacts, such as the product environmental footprint (PEFs) of the European Commission. For this, a standard notation of used materials and manufacturing processes is necessary. Automated environmental assessment and publication of the results, in turn, can facilitate environmentally conscious purchase decisions by end consumers.

Likewise, collecting real end-of-life pathway data allows to find out where products actually end up, and enables feedback loops for improved design of products (in terms of recyclability), and recycling systems (in terms of effectiveness and efficiency). Furthermore, automatically generating reports about recycling quotas of their products with the help of the DLCP would enable producers to fulfil their legal documentation obligations. The DLCP could also help to make environmental effects along the supply chain transparent.

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