Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 122 (2024) 831–836

www.elsevier.com/locate/procedia

31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Connecting Producers and Recyclers: A Digital Product Passport Concept and Implementation Suitable for End-of-Life Management

Christiane Plociennik[a,*], Ali Nazeri[a], Mohammad Hossein Rimaz[a], Svenja Knetsch[b], Alice do Carmo Precci Lopes[c], Tabea Hagedorn[c], Julian Baehr[c], Malte Vogelgesang[c,d], Chanchan Li[d], Wladislaw Benner[d], Bernd Kellerer[e], Emanuel Ionescu[d], Martin Ruskowski[a], Anke Weidenkaff[d]

[a]*German Research Center for Artificial Intelligence (DFKI), Trippstadter Str. 122, 67663 Kaiserslautern, Germany*
[b]*SmartFactory-KL, Trippstadter Str. 122, 67663 Kaiserslautern, Germany*
[c]*Technische Universität Darmstadt, Karolinenplatz 5, 64289 Darmstadt, Germany*
[d]*Fraunhofer IWKS, Brentanostraße 2a, 63755 Alzenau, Germany*
[e]*CIRECON, Jetsam Service Management GmbH, Dr.-Leo-Ritter-Straße 4, 93049 Regensburg, Germany*

* Corresponding author. Tel.: +49 631 20575 3417. *E-mail address:* christiane.plociennik@dfki.de

Abstract

To facilitate the shift from a Linear to a Circular Economy, it is essential to alter the manner in which we manufacture, use, and dispose of products. Interoperable information exchange among various stakeholders throughout the product lifecycle is crucial if we wish to encourage reuse, repair, remanufacturing, refurbishing, or recycling. The Digital Product Passport (DPP) is a concept for capturing product information. This paper presents an end-to-end process for sharing product-related information along the product lifecycle explicitly designed to cater to the needs of all stakeholders, including end-of-life actors. This process is based on a DPP concept and implementation called the *Digital Lifecycle Passport* and a multi-stakeholder platform. Technically, it relies on the Asset Administration Shell (AAS), which enables information to be shared in a structured way. We demonstrate how this process can improve waste sorting and how it can be used for life cycle assessment (LCA). LCA results are captured in an interoperable way based on DIN SPEC 91474, which will facilitate automatic documentation for regulatory purposes in the future. Our approach is a forerunner in the sense that it uses the DPP and the AAS for end-of-life management.

© 2024 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Keywords: Circular Economy; Digital Product Passport; Asset Administration Shell; Digital Lifecycle Passport; Life Cycle Assessment

1. Introduction

In order to arrive at a truly sustainable society, we must shift from a Linear to a Circular Economy. This is, for instance, described in the EU's Circular Economy Action Plan (CEAP [1]). For this to work, exchanging information among the various stakeholders – from production over use, repair, remanufacturing and ultimately recycling a product – is crucial. Hence, one key instrument for the implementation of the Circular Economy is the Digital Product Passport (DPP), as envisioned in the Ecodesign for Sustainable Products Regulation (ESPR [2]). The DPP is designed to serve as an information hub for all stakeholders in the Circular Economy.

Currently, the earlier lifecycle phases like production and usage are well understood from a DPP perspective: Which information does a consumer require, for instance, to be able to make an informed decision on whether to buy a specific product or rather consider an alternative? The later lifecycle phases, like repair, remanufacturing, refurbishment or recycling, however, are less in the focus at the moment, although they can probably benefit most from the DPP: If the DPP provides, for instance, information on how to disassemble or repair a product, this can greatly ease the work of the stakeholders concerned with these tasks. What is lacking, at the moment, is a coherent end-to-end process that makes the adoption of the DPP feasible over all lifecycle phases, including product end-of-life.

In this paper, we present a multi-stakeholder DPP concept and implementation along with a platform for the structured sharing of information. It makes use of the Asset Administration Shell (AAS), an information (meta-)model rooted in manufacturing, but not yet widely used during later lifecycle phases.

2212-8271 © 2024 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 31st CIRP Conference on Life Cycle Engineering (LCE 2024)
10.1016/j.procir.2024.02.026

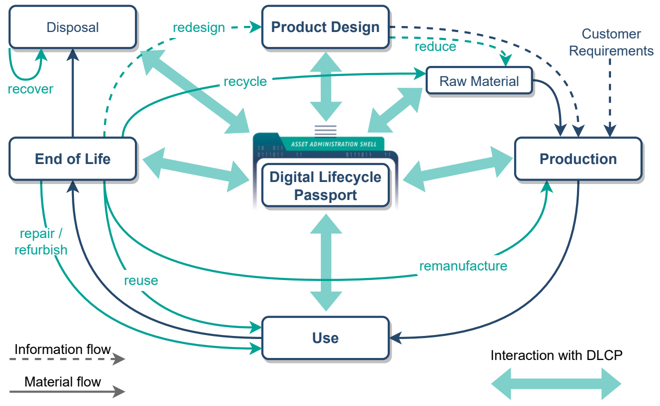


Fig. 1. The DLCP facilitates communication in the Circular Economy.

We demonstrate on an e-waste sorting use case how all stakeholders can benefit from a DPP based on AAS and hence that AAS is well suited for end-of-life processes. We also show how to perform life cycle assessment (LCA) and how to write back LCA results in an interoperable way based on DIN SPEC 91474. We call our flavor of DPP the *Digital Lifecycle Passport* (DLCP) as it explicitly caters to end-of-life processes (see Figure 1).

This paper is structured as follows: Section 2 discusses related work, Section 3 introduces the usecase and shows how it guides the development of the DLCP, its platform and the AI-based waste sorting mechanism. Section 4 sketches a method to perform LCA based on the DLCP and shows how to capture the results in AAS format in a standardized way, and Section 5 concludes the paper.

2. Related Work

2.1. Digital Product Passport & Platform

From a legal perspective, the DPP is being shaped in several regulation documents and directives, the most prominent being the European Green Deal [3] and the Circular Economy Action Plan [1]. The first mandatory DPP is planned for batteries. The European directive calls for the establishment of an electronic exchange system and a DPP (or "Battery Passport") for every industrial battery and traction battery with a capacity of more than 2 kWh [4].

From an implementation perspective, several endeavors exist that are concerned with DPPs or similar concepts (see [5] for a comprehensive overview). Some pursue a cross-sectoral approach [6, 7, 8], while others are conceptualized in a sector-oriented way [9, 10]. All of them are either at the conceptual level [11], in a prototypical stage [12, 7] or are being tested in first pilots on the market [13]. The solutions range from PDF files that are sent to a stakeholder upon request [12] to solutions that can be accessed via an API and provide different output to different (human and machine) actors. Solutions based on the Asset Administration Shell (AAS) [14] are of particular interest here, since this solution builds on a solid technical base originating from Industry 4.0. Furthermore, it is advocated by a growing number of parties [15, 16]. However, it is not yet established for end-of-life processes.

2.2. AI-based Sorting

According to the Global E-waste Monitor [17], approximately 53.6 million metric tons of e-waste were produced in 2019. Due to the complex components of e-waste, the sorting processes are usually ineffective and recycling rates are quite low. Hagel [18] states that the overall gold recycling rate from e-waste reached only 33%. In this case, sensor-based sorting is utilized to improve the performance [19, 20]. State-of-the-art sorting machines are equipped with sensors such as near-infrared, visible spectrum, ultra-violet or magnetic induction. Sensor fusion object detection refers to the integration of data from multiple sensors in order to enhance the accuracy and robustness of the detection. Further, object detection allows to extract devices containing gold, leading to an increased gold recycling rate. Various sensor fusion approaches and techniques have been proposed, considering different levels of fusion [21]. Choosing the right architecture depends on factors like the types of sensors and the available computational power [22].

2.3. End-of-Life Assessment

There are a variety of assessment frameworks and guidelines to assess the greenhouse gas emissions (GHG) of products, services and organizations. The most prominent examples are the life cycle assessment for products and services based on [23] and [24]; the Product Environmental Footprint (PEF) [25] for products; and the Organisational Environmental Footprint [25] and GHG Protocol Corporate Standard [26] for organizations. The assessment of GHG emissions, regardless of the application field, requires trained experts due to the modelling and data acquisition complexity. In the field of waste management, the EASETECH software enables assessing complex processes handling heterogeneous material flows [27]. To facilitate GHG emission assessments, there are also user-friendly tools for non-experts on LCA, such as ecocockpit [28] for organizations and CYCLOPS [29] for stakeholders of the recycled plastics industry. However, there is still the need to develop a user-friendly tool for non LCA-experts to support stakeholders handling small electrical and electronic appliance waste.

3. Materials and Methods

3.1. Use Case: Sorting of Small Electrical Appliances

To demonstrate the capabilities of the DLCP, it is applied to the sorting task of waste from electrical and electronic equipment (WEEE) (see [7] for details) – more precisely, small household appliances and small devices of information and communications technology from the German collection group 5. Currently, the devices are manually sorted for individual treatment processes by specialized companies. A goal for the combination of DLCP and AI-based sorting is to automate the labor-intensive manual sorting process. The DLCP is used to provide information about the contents and therefore treatment requirements for WEEE devices. It is implemented in an AI-supported sensor-based sorting machine to demonstrate the support of end-of-life treatment with these technologies. Hence, the DLCP adds information to the sensor data. The sorting machine is part of a pilot plant located at the German research institution Fraunhofer IWKS with different processes in a small industrial scale. Five categories of devices were selected for the trials, consisting of smartphones, key-operated mobile phones, digital cameras, routers, and batteries. The sorting machine separates the material stream in one passing (pass/reject) and one ejected (eject) fraction. Two sorting steps are necessary: In the first sorting step, all devices that require manual pollutant removal are ejected. The second step separates all devices that contain components too valuable for mechanical treatment. The devices are fed into the sensor-based sorting machine (Figure 2) via a vibration feeder and accelerated on a conveyor belt. They pass 3 different sensors: First, an inductive sensor measures the conductivity of particles, detecting metals and other conductive materials. Then, a hyperspectral near-infrared (NIR) camera distinguishes material characteristics of polymers, such as plastics, paper, or wood. An optical line scan camera then records RGB data.

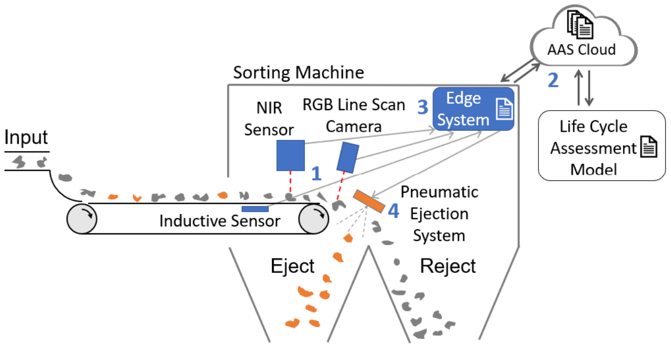


Fig. 2. Representation of mass flow and information flow in the WEEE sorting use case.

In this usecase, the data flow is as follows (see Figure 2): Data from the RGB camera flows into a neural network-based object detector (SSD512), connecting the physical system of the sorting machine and the virtual object detection (1) – cf. Section 3.3. This network recognizes the type of each device, linking the physical objects on the conveyor belt to their digital representation in the DLCP (2). The sorting system can then query information about the critical components and material composition of the device from the DLCP. This information is analyzed according to the specific sorting task (3). If it matches the criteria, a signal is sent to the ejection system, opening valves to send a jet of compressed air, ejecting the object from mid-air after leaving the conveyor belt (4).

3.2. DLCP for Smartphones & Platform

As mentioned above, the goal of the DLCP is to create a structured way to store and retrieve information for multiple stakeholders. For this purpose, a cloud-based platform has been developed (see [30] for details). This platform provides role-based access to the DLCP for all stakeholders. It can be used by humans and machines (like the waste sorter in our usecase). Information is structured in AAS based on so-called Submodels. An example AAS for a smartphone is depicted in Figure 3.


Asset AssetInformation https:/smartfactory.de/ids/asset/Smartphone
SM "Identification" V2.0 [https://smartfactory.de/ids/sm/7410_2290_2112_3232]
SM <T> "GS1" [https://example.com/ids/sm/9163_4132_2032_5675]
SM <T> "Barcode" [https://example.com/ids/sm/4553_4132_2032_2905]
SM "DeviceSpecification" V0.5 [https://smartfactory.de/ids/sm/8475_2290_2112_3022]
SM <T> "LifeCycle" V2.0 [https://smartfactory.de/ids/sm/4520_2290_2112_9770]
SM "CatalogueOfLaws" V1.0 [https://smartfactory.de/ids/sm/8330_2290_2112_9483]
SM "Hazard" V1.0 [https://smartfactory.de/ids/sm/5530_2290_2112_6842]
SM "BillOfMaterial" V0.3 [https://smartfactory.de//ids/sm/1540_2290_2112_2117]
SM "ProductComponents" V0.3 [https://smartfactory.de//ids/sm/5451_9051_7022_3151]
  BOM Bill of Material - Graph display ready
  Ent "Smartphone"
  Ent "Battery"
  Ent "Display"
  Ent "Camera"
  Ent "Memory"
SM "LevelStructureOfTheSBOM" V1.0 [https://smartfactory.de/ids/sm/1285_6060_9022_1613]
SM "BillOfMaterialDocument" V1.0 [https://smartfactory.de/ids/sm/2120_7060_9022_0353]
SM <T> "CarbonFootprint_CirPass" [https://example.com/ids/sm/9561_2130_2032_1235]
SM <T> "MaterialComposition" [https://example.com/ids/sm/4083_0102_2122_4324]
SM <T> "EndOfLifeInformation" [https://example.com/ids/sm/5055_2130_2032_3790]
SM <T> "CarbonFootprint" [https://industrialdigitaltwin.org/ids/sm/ProductCarbonFootprint]
SM <T> "TechnicalData" V1.2 [https://admin-shell.io/ZVEI/TechnicalData/Submodel/1/2]
SM <T> "LifecycleRecord_Metadata" [https://example.com/ids/sm/8522_8010_2032_2908]

Fig. 3. AAS for smartphone.

We conducted an evaluation of the platform with 20 individuals from an engineering background, encompassing disciplines such as computer science, mechanical engineering, and industrial engineering. The majority of participants possessed a basic familiarity with Digital Twins, and they were able to comprehend the platform's concepts efficiently and navigate to perform various tasks. Participants generally considered the system to be intuitive and user-friendly after overcoming the initial learning curve. However, concerns were raised regarding data security, and there is a perceived need for more robust filtering and search options. Some participants expressed positive feedback regarding the incorporation of sections for product life cycle assessment and recognized the value in utilizing AAS for DPPs. With regard to the user interface (see Figure 7), the participants expressed a desire for a more modern, intuitive design, clearer visual feedback, and streamlined interaction elements.

3.3. AI-based Sorting

Two different approaches for sensor fusion object detection are utilized for sorting: **Concatenation** and **Image Mirroring**. The first approach concatenates image data with data from a hyperspectral near-infrared camera (NIR) and an inductive sensor (5-B). The second approach relies on a specific combination of NIR and inductive sensor data to simulate the structure of image data containing three channels (RGB). In this Siamese architecture, which can be considered a twin network, the models are

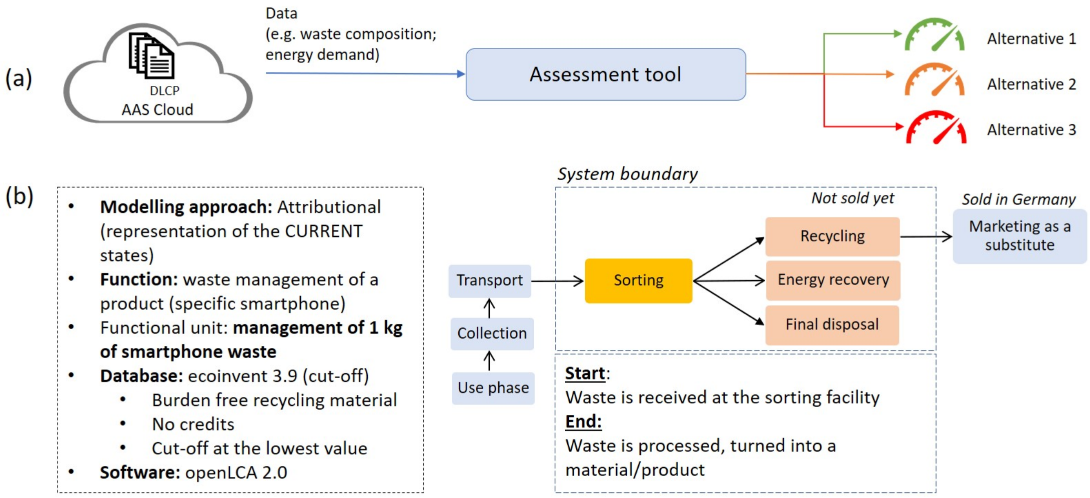


Fig. 4. Overview of the end-of-life assessment method concept. (a) Use of data from the DLCP to feed the assessment tool; (b) Overview of the methodological choices to build the assessment method.

trained simultaneously with shared weights, enabling them to collectively learn and represent the data effectively (5-C). Figure 5 illustrates the base model (5-A) besides two sensor fusion approaches (5-B and 5-C).

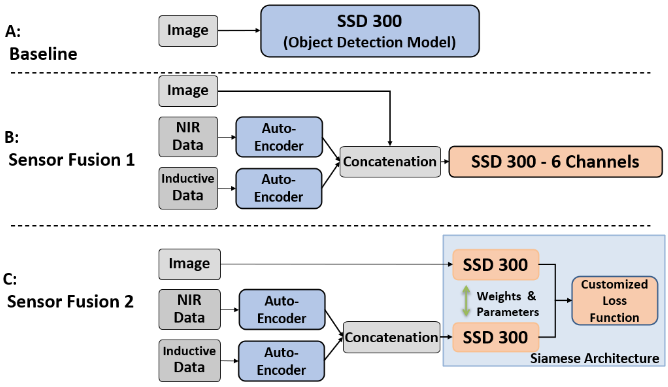


Fig. 5. Model Architectures

The two sensor fusion approaches, Concatenation and Image Mirroring, improve the mean average precision (mAP) from 0.777 (baseline model) to 0.859 and 0.841, respectively. The result shows that the integration of multi-sensor data can improve the object detection significantly (see [31] for details).

The time passing from gathering sensor data and ejecting the objects meeting the sorting requirements in commercial systems is rather low (< 100 ms). A sorting system that runs at an industrial scale needs suitable hardware to fulfill the machine learning model decisions in a short time and also be consistent in its object classification. Newly designed systems might consider a longer distance between sensors and ejection nozzles to make sure that the neural network has enough time to classify as many objects correctly as possible.

3.4. Writing back Sorting Data into Cloud

Interaction with the cloud platform is not limited to a user interface, but can also be achieved via a REST API. An edge system deployed on the sorting facility can retrieve the necessary information and utilize it for sorting decisions (see Figure 2). Additionally, data related to the sorting process, such as energy consumption, duration, and waste processing methods, can be written back to the DLCP and be used by other stakeholders.

4. End-of-Life Assessment

The DLCP provides a variety of possibilities to boost the Circular Economy. We propose the concept of an assessment method to be integrated into a tool for non-expert LCA users to support decisions at the end-of-life stage using data provided by the DLCP. The assessment method has been first conceptualized for stakeholders treating smartphone wastes and waste brokers [32]. Currently, waste brokers are mediators, matching waste management companies with waste producers, so that the waste producer fulfills waste management obligations. With the transition to a circular and digitalized economy, waste brokers will process a higher amount of data and information, not only mediating but finding out the best waste management options with the least potential environmental impacts. Hence, our end-of-life assessment method has the potential to provide decision support to waste brokers.

Our assessment method addresses the following question: “According to which ”basket of goods” should the sorting for small electrical appliances, specifically, smartphones, be optimised based on Global Warming Potential?” From the discussion with potential users, the following criteria for the development of the assessment method were derived: **Comparability**: The assessment should enable the comparison of GHG emissions by the change of the baskets after sorting; **Simplicity**: The assessment should lead to the identification of optimisation

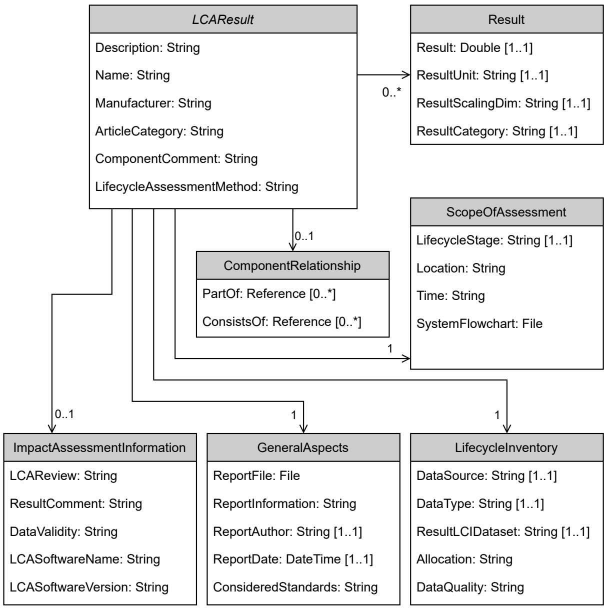
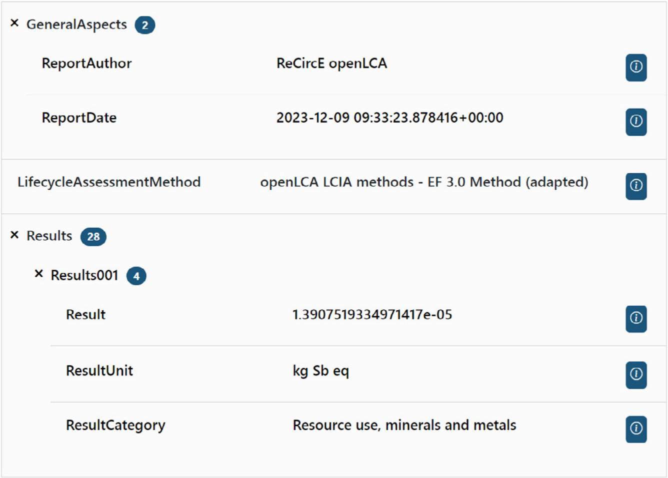


Fig. 6. UML diagram for LCA result based on DIN SPEC 91474.

possibilities in waste treatment with a reasonable effort; **Conservatism**: The assumptions and ultimately the results need to be conservative, i.e. the savings quantities are not overestimated by arbitrary assumptions. The specification of the assumptions plays a central role and must be documented; **Standardization**: The assessment method requires a high degree of standardisation, both in terms of the calculation steps and the underlying assumptions and data used; **Flexibility**: The assessment method should be supplemented and expandable in its consideration of possible disposal routes and substitution assessments; and **Customizability**: It should be possible to deviate from the specifications and reference values for one's own purpose.

Based on the above-mentioned criteria, the concept of the assessment method was developed (see Figure 4). It allows the user to create his/her own waste management alternatives and compare them with regard to potential greenhouse gas (GHG) emissions. The results of each scenario are presented as a color scale: red means that the results are worse than the baseline alternative, green means better. Based on data provided by the DLCP and data provided by the user, different scenarios can be compared with regard to potential GHG emissions (Figure 4a).

The assessment method has been designed mainly for waste brokers and sorting facilities treating smartphone wastes as first potential users. Therefore, the available options in the assessment method include: materials and components (e.g. glass, metals, plastics, batteries; auxiliary materials); sorting processes (NIR based sorting, wind sifting and shredder); recycling processes (e.g. hydrometallurgical process; pyrometallurgical process; refining, cast-alloy; remelting, wrought alloy; refining non-metallurgical); energy recovery and final disposal (Figure 4b). In a next step, the method can be extended to include other stakeholders, e.g. at the design stage of a product.


× GeneralAspects 2

ReportAuthor	ReCircE openLCA	ⓘ
ReportDate	2023-12-09 09:33:23.878416+00:00	ⓘ
LifecycleAssessmentMethod	openLCA LCIA methods - EF 3.0 Method (adapted)	ⓘ

× Results 28

× Results001 4

Result	1.3907519334971417e-05	ⓘ
ResultUnit	kg Sb eq	ⓘ
ResultCategory	Resource use, minerals and metals	ⓘ

Fig. 7. LCA result in web application user interface.

4.1. *Interoperable Life Cycle Assessment Result*

A uniform presentation of environmental product data is a crucial prerequisite for evaluating products based on their environmental impact. DIN SPEC 91474 [33] serves as the foundation for our modeling, enabling interoperable information exchange. Figure 6 shows the derived UML diagram, which is then modeled as an AAS Submodel. Within our cloud application, we perform an LCA using openLCA [34], and write back the calculated results based on the created template, as depicted in Figure 7.

5. Conclusion and Outlook

In this paper, we have shown how to use our multi-stakeholder DPP concept and implementation based on the Asset Administration Shell, the Digital Lifecycle Passport, for end-of-life management. We have employed it for the sorting of e-waste, sketched a process for LCA based on the DLCP, and shown how the DLCP can be employed for capturing the LCA results in a standardized, interoperable format based on DIN SPEC 91474.

The evaluation of the platform provided valuable insights into the usability and challenges of the system. While users generally found the platform easy to use, some expressed concerns about the complexity of the LCA part and suggested improvements to make it more user-friendly for daily business.

The idea of a comprehensive DPP such as the Digital Lifecycle Passport designed here, whose data is also available to those involved in the end-of-life of a product and can be used (e.g. via AAS), is an important step towards the Circular Economy. Companies from the waste management sector can thus act and document more effectively, transparently and in a more targeted manner, as is also shown conclusively on the basis of the usecase. This way, information can be created and made available for all parties in the life cycle of a product. Findings from the treatment of the product at the end-of-life allow conclusions to be drawn that could, for example, contribute to a more circular product design or be used to control and improve the environmental impact of a product.

Once a product has reached the end of its life, the question arises of how to deal with the waste. Of course, data from a DPP can influence this decision. Specific information is needed to choose the most appropriate treatment method in terms of sustainability and economic efficiency. Here, end-of-life specific extensions or even additional Digital Passport systems could be helpful. For example, a Resource/Material Passport could be used to anticipate the quantities of secondary raw materials that can be generated and compare them to other treatment methods. The process and efficiency of these options could additionally be documented by a Process Passport for further use.

Acknowledgements

This work is funded by the BMUV, project Green-AI Hub, grant number 57-E-2110, and project ReCircE, grant number 03EN2353B. We thank Manuel Reif for Figure 1.

References

[1] The European Commission, A new Circular Economy Action Plan For a cleaner and more competitive Europe (2020).
URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:98:FIN

[2] European Commission, Proposal for Ecodesign for Sustainable Products Regulation (2022).
URL https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en

[3] The European Commission, The European Green Deal (2019).
URL https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

[4] European Parliament, Batteries Regulation (2023).
URL https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542

[5] C. Plociennik, M. Pourjafarian, S. Saleh, T. Hagedorn, A. d. Carmo Precci Lopes, M. Vogelgesang, J. Baehr, B. Kellerer, M. Jansen, H. Berg, et al., Requirements for a Digital Product Passport to Boost the Circular Economy, INFORMATIK 2022 (2022).

[6] GS1 in Europe, Proposed Architecture and Principles for Digital Product Passports (2022).
URL https://gs1.eu/wp-content/uploads/2022/08/Digital_Product_Passport_Architecture_GS1inEurope_March_2022.pdf

[7] C. Plociennik, M. Pourjafarian, A. Nazeri, W. Windholz, S. Knetsch, J. Rickert, A. Ciroth, A. d. C. P. Lopes, T. Hagedorn, M. Vogelgesang, et al., Towards a Digital Lifecycle Passport for the Circular Economy, Procedia CIRP 105 (2022) 122–127.

[8] M. Jansen, T. Meisen, C. Plociennik, H. Berg, A. Pomp, W. Windholz, Stop Guessing in the Dark: Identified Requirements for Digital Product Passport Systems, Systems 11 (3) (2023).

[9] Global Battery Alliance (GBA), Battery Passport (2023).
URL https://www.globalbattery.org/battery-passport/

[10] Madaster Foundation, Madaster (2023).
URL https://madaster.de/

[11] Y. Bai, N. Muralidharan, Y.-K. Sun, S. Passerini, M. S. Whittingham, I. Belharouak, Energy and environmental aspects in recycling lithium-ion batteries: Concept of Battery Identity Global Passport, Materials Today 41 (2020). doi:10.1016/j.mattod.2020.09.001.

[12] The Circularity Dataset Initiative, PCDS (2022).
URL https://pcds.lu/pcds-system/#pcds

[13] circular.fashion UG, circularity.ID® Open Data Standard V2.0 (2020).
URL https://circularity.id/static/circularity.ID-Standard-Specification-v2.pdf

[14] Plattform Industrie 4.0, Details of the asset administration shell, part 1 - the exchange of information between partners in the value chain of industrie 4.0 (version 3.0rc02), Tech. rep., Plattform Industrie 4.0 (05 2022).
URL https://www.plattform-i40.de/IP/Redaktion/EN/Downloads/Publikation/Details_of_the_Asset_Administration_Shell_Part1_V3.html

[15] Industrial Digital Twin Association e.V., DPP 4.0 – The Digital Product Passport for Industrie 4.0 (2023).
URL https://dpp40.eu/

[16] DKE, Digital Product Passport: Promoting Digitalisation and the Circular Economy Through Standardised Data [Press release] (2023).
URL https://www.dke.de/en/areas-of-work/industry/digitaler-product-passport

[17] Forti V., Baldé C.P., Kuehr R., Bel G., The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential (2020).

[18] C. Hagelüken, D. Goldmann, Recycling and circular economy—towards a closed loop for metals in emerging clean technologies, Mineral Economics 35 (3-4) (2022) 539–562.

[19] V. Forti, C. P. Balde, R. Kuehr, G. Bel, The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential (2020).

[20] N. Kroell, X. Chen, K. Greiff, A. Feil, Optical sensors and machine learning algorithms in sensor-based material flow characterization for mechanical recycling processes: A literature review, Waste Management (2022).

[21] J. Cai, Z. Meng, A. S. Khan, Z. Li, et al., Feature-level and model-level audiovisual fusion for emotion recognition in the wild, in: Conference on Multimedia Information Processing and Retrieval, IEEE, 2019.

[22] D. J. Yeong, G. Velasco-Hernandez, J. Barry, J. Walsh, Sensor and Sensor Fusion Technology in Autonomous Vehicles: A Review, Sensors 21 (6) (2021) 2140.

[23] DIN EN ISO 14040:2006, Environmental management: Life cycle assessment - Principles and framework.

[24] DIN EN ISO 14044, Environmental management: Life cycle assessment –Life cycle assessment – Requirements and guidelines (ISO 14044:2006 + Amd 1:2017 + Amd 2:2020).

[25] European Platform on LCA — EPLCA (08.09.2023).
URL https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html

[26] WRI and WBCSD, Corporate Standard — GHG Protocol (2023).
URL https://ghgprotocol.org/corporate-standard

[27] DTU, EASETECH: Model description (2023).
URL http://www.easetech.dk/da/model-description/technology-modelling

[28] ecocockpit, ecocockpit – CO2-Bilanzierung für Unternehmen.
URL https://ecocockpit.de/

[29] CYCLOPS. A Toolbox for Buyers and Sellers in the Recycled Plastics and Plastic Waste Industry (2023).
URL http://cyclops.greendelta.com/

[30] M. Pourjafarian, C. Plociennik, M. H. Rimaz, P. Stein, M. Vogelgesang, C. Li, S. Knetsch, S. Bergweiler, M. Ruskowski, A Multi-Stakeholder Digital Product Passport Based on the Asset Administration Shell, ETFA 2023 - Second Workshop on Implementing Asset Administration Shells (ImplAAS) (2023).

[31] A. Nazeri, C. Plociennik, M. Vogelgesang, C. Li, M. Ruskowski, A Novel Approach for Sensor Fusion Object Detection in Waste Sorting: The Case of WEEE, EnviroInfo 2023 (2023).

[32] T. Hagedorn, A. do Carmo Precci Lopes, L. Schebek, M. Vogelgesang, W. Benner, C. Li, C. Plociennik, Hossein, S. Knetch, B. Kellerer, The practical use of a digital product passport - Development of an application-friendly tool for e-waste decision support.
URL https://members.sardiniasymposium.it/pdf_sardinia2023/2291_Hagedorn.pdf

[33] DIN SPEC 91474:2023-02. doi:10.31030/3406982.
URL https://doi.org/10.31030/3406982

[34] openLCA, https://www.openlca.org (2023).