Value assessment of consumer electronics with Digital Product Passports: A case study of lifetime extension assessment of disposed washing machines

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Abstract. The rapid increase in e-waste poses significant environmental challenges. Most disposed Electrical and Electronic Equipment (EEE) products, including computers, mobile phones, and household appliances, are currently recycled for materials rather than reused, due to perceived low residual value. This approach conflicts with circular economy goals, which emphasize extending product lifetimes. Many disposed EEE items are "end-of-use" rather than "end-of-life," indicating potential for reuse after refurbishment or repair. However, effective lifetime extension is hampered by inadequate data sharing and complex data systems within the EEE sector. This research addresses the data-sharing problem essential for circular strategies and improving EEE lifetime extension. Digital transformation, particularly through Digital Product Passports (DPPs), can facilitate comprehensive product lifecycle management, supporting sustainable practices. We propose an EEE ecosystem modelling approach to compare traditional and circular business models through e3-value models, focusing on washing machines. We investigated the applicability of DPPs to aid decision-making for lifetime extension at collection points.

Keywords: Circular Ecosystem, Lifetime Extension, Digital Product Passport, E-Waste, Electrical and Electronic Equipment.

1 Introduction

The waste flow from disposed Electrical and Electronic Equipment (EEE), or e-waste, is one of the fastest growing waste streams[1]. EEE refers to products such as heaters and coolers, computers, screens and monitors, mobile phones, lamps, white goods, and household appliances. According to the Global E-waste Monitor 2024 Forti, Balde [1], the amount of e-waste worldwide was 62 billion kilograms in 2022 and is expected to increase to 82 billion kilograms by 2030. Most disposed EEE products are treated as e-waste with little residual technical and economic value to justify reuse. Materials recycling is the preferred strategy for handling the e-waste stream.

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1 https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en

Product lifetime extension of EEE is a critical lever to diminish e-waste and utilize the residual value of disposed EEE. However, the current focus on materials recycling is at odds with the ambitions of governments to work towards a circular economy promoting product lifetime extension [2]. A critical factor that complicates lifetime extension is that disposed EEE devices are currently treated as "end-of-life" products. Such products lost their structural performance and are considered as obsolete [3]. In many cases, however, it is questionable whether a disposed EEE product is functionally and technically obsolete [4]. Consumers tend to stop using a product if they can afford a new product with better performance, more functionality, or higher visual attractiveness. The disposed product in these cases is often "end-of-use" rather than "end-of-life", and lifetime extension could initiate a new use cycle with another user until the product reaches the next end-of-use (or ultimately, end-of-life).

Lifetime extension implies a decision that the residual value of a product justifies another use cycle, possibly after necessary refurbishment or repair. However, obtaining the necessary data for easy and objective decision-making is hampered by characteristics of the EEE sector, including lack of data sharing across supply chains and complex data systems [5].

The goal of this paper is to address the problem of data sharing for circular strategies in the EEE sector and especially for improving lifetime extension of EEE.

A business barrier for data sharing is the lack of business incentive for making data available. Due to the absence of an EEE ecosystem perspective that provides insights in new circular business models based on collaboration, individual EEE businesses are reticent when it comes to making investments regarding data sharing that make such collaboration possible. Collaboration between different actors in an ecosystem is necessary to develop a joint circular value proposition [6-8]. Therefore, we propose in this paper an EEE ecosystem modelling approach to represent and compare traditional and circular strategy business models based on collaboration between various actors. We focus on washing machines as a specific EEE sector in which the lifetime extension of goods is important, yet currently at best only partially successful. We aim to address some of the issues behind the slow progress of in this sector, especially the current lack of residual value recognition of disposed goods by collection agents (i.e., organizations that offer e-waste collection services at some physical location).

Next to the business barrier, technical barriers exist with respect to data sharing in the EEE sector. Not only are data systems within and across EEE supply chains incompatible [5], there is also no clear roadmap on deciding which data to share, how to share the data, and how to use the data for circular strategies including lifetime extension. Digitalization and digital transformation are important enablers of making better and more efficient use of (digital) data, but these developments do not necessarily lower the technical barriers. One application enabled by digital transformation, namely the digital product passport (DPP), might help to develop a focus on choosing, sharing and using data in the EEE sector. A DPP collects and makes available product data throughout the product's entire lifecycle, which can facilitate sustainable product life cycle management in a circular value chain [9].

In this paper, we investigate the applicability of a DPP for the EEE sector. Again, we focus on washing machines as a specific EEE sector and we look at the use of DPP data to support decision-making for lifetime extension of washing machines at collection agents. As a source of inspiration and to acquire a baseline for required data, we also study the current practice of lifetime extension of washing machines. Furthermore, we suggest to use an ecosystem perspective, e.g., as supported by our EEE ecosystem modelling approach, as a starting point to identify required data for desired collaboration in a selected business model. Based on this, we propose information categories to include in the DPP and a decision process blueprint that could be implemented at collection agents.

The remainder of the paper is organized as follows: Section 2 provides useful background on the economic and technical topics related to the e-waste problem; Section 3 discusses an ecosystem perspective on the washing machines sector that allows analysis of the current value chain and projecting circular alternatives; Section 4 presents results of field studies on lifetime extension of washing machines in current practices; Section 5 proposes a digital transformation based on a digital product passport for washing machines and decision support at collection points; Section 6 relates the results to an ecosystem of the future, while identifying the need for a suitable infrastructure to support data sharing; and Section 7 presents our concluding remarks.

2 Background

2.1 Circular ecosystems

Long-term collaborative relations with partners in a network and transparency of information across supply chains greatly facilitate the implementation of a circular economy in the EEE sector [5]. Nonetheless, a circular economy requires an ecosystem innovation based on circular principles that address circular strategies [7]. Collaboration between different actors in such a circular ecosystem is necessary to develop a joint circular value proposition from a product life cycle perspective that integrates lifetime extension.

A circular ecosystem is a "a co-evolving, dynamic and potentially self-organizing configuration, in which actors integrate resources and co-create circular value flows in interaction with each other." [10] A circular ecosystem aligns the multilateral dependencies and complementarities among actors in a value network in order to maximize a collective value proposition where the whole acts as one unit [6, 11]. Thus, ecosystem actors achieve joint circular strategies and goals because their activities are jointly coordinated; they act interdependently and carry them out together [7].

Digital technologies and data play a crucial role in circular ecosystems [8]. They are enablers of data integration and sharing, which in turn support informed decision-making and value creation [10]. Orchestration and governance mechanisms can be used to structure the data sharing, collaboration, and value sharing amongst circular ecosystem actors. The vitality and innovation of circular ecosystems does not only depend on technology enablers and business motivation, but is also affected by factors such as initial context of the ecosystem, legislation, environmental pressures, trust among ecosystem actors, and product properties [12].

2.2 Circularity and lifetime extension

Circularity can be realized by slowing, narrowing, and closing resource loops [13-15]. ‘Slowing’ is achieved by designing long-life products and by product lifetime extension, ‘narrowing’ by reducing the use of resources, and ‘closing’ by recycling components or materials for use in a new product life cycle. Here, product lifetime is understood as “the useful life of a product; the time during which the product remains integer and usable for its primary function for which it was conceived and produced” [16].

The concept of circular economy relates closely to the waste hierarchy of ‘4Rs’: Reduce, Reuse, Recycle, and Recovery [17]. These Rs play the role of circular strategies, which have to prioritized and properly ordered to make an efficacious circular economy ecosystem [18, 19]. As part of slowing resource loops, product lifetime extension aims to prolong the useful life of products [16]. The Reuse strategy and substrategies, such as Repair, Refurbish and Remanufacture, aim to extend a product’s lifetime and its parts [20]. Maximizing lifetime by designing long-life products and encouraging the reuse of products, parts, and materials ensures that the economic and environmental value of EEE products is preserved for as long as possible and prevents unnecessary value destruction. The product lifetime and the extension of EEE depends on various product-related, use-related, service-related and circumstantial factors. These factors need to be considered when defining lifetime extension assessment criteria. For example, the lifetime of washing machines depends on factors such as mechanical stress, abrasion, performed maintenance activities, new technologies, aesthetics, energy efficiency, and environmental conditions [21, 22]. EEE’s repairability also affects lifetime extension. Repairability is the ability and ease with which a product can be repaired during its life cycle [23]. The corresponding repairability score is determined by information provision, product design for repair (e.g., modular and standardized design, ease of disassembly), and supportive services (e.g., spare part supply) [24].

An environmental impact assessment should be carried out to assess the possible extension of the lifespan of energy-using EEE products [25]. For washing machines, water and energy efficiency determine environmental impact highly [26]. Therefore, a life cycle analysis is required, assessing the environmental impact of EEE on quantified CO2 emissions for the whole life cycle [27-29]. Another consideration is that Internet of Things technologies are a driver for circular innovation of the washing machine industry ecosystem [30, 31].

2.3 Digital Product Passport

The EU Green Deal Action plan sees digitization of product information throughout the entire product life cycle as an enabler towards a circular economy [32]. A DPP contains unique product identifiers allowing data storage, retrieval, and sharing by various value chain actors throughout the product lifecycle [33]. Consequently, DPPs can support sustainable product life cycle management and value retention in a circular value chain [34, 35]. DPP is a promising instrument to gather and share product data for decision-making [36, 37] and addressing currently existing information asymmetries [34, 38, 39].

A common definition of DPP is "a product-specific data set, which can be electronically accessed through a data carrier to electronically register, process and share product-related information amongst supply chain businesses, authorities, and consumers" [40]. The information in the passport relates to the product's environmental sustainability and is, therefore, relevant for resource-efficient, sustainable, and circular production and consumption systems [41, 42]. DPPs support end-of-use circular strategies [40]. The reuse of products can be determined more accurately because the data in a DPP will objectify the residual value of the products. Repair and maintenance can be better predicted and programmed over time. Detailed technical, repairability, product, usage, and spare parts information contribute favorably to lifetime extension services provided by repairers and maintenance service providers [33].

Recently, several DPP initiatives were introduced for specific product categories [35], such as electric vehicle batteries [9], textile products [43], and construction products [44]. However, many DPP initiatives emphasize an individual stakeholder in a value chain or an industry instead of assuming an integral ecosystem perspective that involves all stakeholders [35]. The fragmentation of the desired data across multiple value chain actors and data sources hinders DPP creation and handling [37]. Therefore, the DPP orchestration should be positioned in a Digital Product Passport Ecosystem that enables different DPP applications for different stakeholders in value networks [45, 46]. Such a DPP ecosystem requires an underlying digital infrastructure and standardized data governance requirements that enable data sharing among stakeholders in the ecosystem [47].

3 EEE ecosystem

Several actors can be identified in the current EEE ecosystem. Forward supply actors such as manufacturers and retailers strive for operational efficiency, technical product innovation, and profit maximization by selling new EEEs. Consumers mainly strive for low prices. After usage, they strive to dispose their EEE efficiently. Consequently, EEE lifetime extension is not a key driver of these actors, resulting in a large flow of low-quality EEE. Affected by the extended producer responsibility, manufacturers and retailers delegate reverse supply chain activities to Waste from Electrical and Electronic Equipment (WEEE) management centers. As part of the reverse supply chain, collection agents and WEEE management take care of reverse logistics and the collection, sorting, dissembling, and administration of discarded EEE. Subsequently, recycling companies focus on materials recycling. A fixed fee based on the weight of collected EEE favors materials drive recycling. On a minor scale, repair facilities restore end-of-use EEE into working order.

We developed a current and envisioned EEE ecosystem specialized for washing machines using the e3-value modeling language. *E3-value* is a language to build and analyze value networks [48]. An e3-value model represents a value network in which actors exchange value objects, resulting in a benefit for each actor. The set of value transfers in a value network results in a collective value proposition that meets the customer's needs.

Figure 1.a presents the e3-value model of a value network corresponding to the current washing machine market. In short, the e3-value graphical notation used in the models presented here includes: actor (square), value activity (rounded square), value transaction (connector), value interface (two opposite arrows within an ellipse), customer need (circle with dot) and boundary element (circle with 'x'). Figure 1.a shows how a consumer's need motivates a collection of value exchanges to satisfy the need. The financial and product-oriented value exchanges encourage consumers, retailers, manufacturers, materials, and component suppliers to participate in the value network.

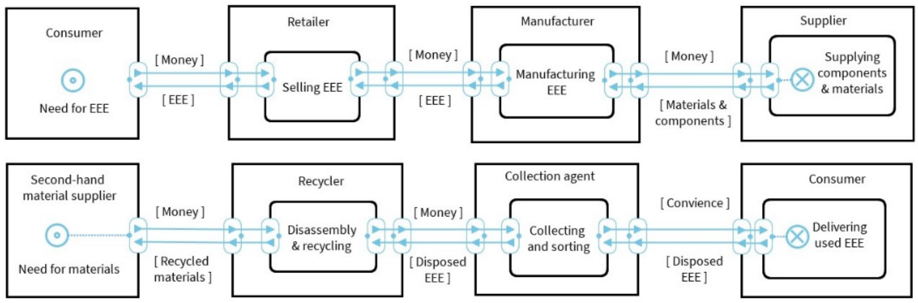

Fig.1. Value networks of current EEE ecosystem: **a)** Satisfying the need of a consumer of having a (functioning) washing machine; and **b)** satisfying the need of a second hand material supplier to have second hand (components and materials of) washing machines that can be offered for sale.

Figure 1.b shows that a supplier's need for second-hand materials motivates financial and material value exchanges among suppliers, recyclers, collection agents, and consumers. Our modeling process showed the necessity of developing two separate value network models. Namely, second-hand material suppliers in figure 1.b purchase materials that are not reused to manufacture new washing machines but are applied for other recycling purposes.

The modeled value networks clarify that the value exchanges between actors are only economically attractive to them when selling new EEE or recycling materials. Value exchanges based on product lifetime extension are not economically attractive for them. Insufficient EEE ecosystem orchestration, interconnected actors across the ecosystem, aligned actors' interests to act circularly, co-creation of circular value flows, capabilities to identify EEE's residual technical and economic value, and data sharing hamper collective circular value propositions aiming to extend the lifetime of EEE.

Lifetime extension of discarded EEE is a collective task of the actors in the ecosystem. To tackle the abovementioned barriers, we propose a future e3-value model that strives for more lifetime extension of disposed washing machines (see Figure 2). We choose the perspective of a collection agent who has a critical role in identifying the residual value of collected EEE and harvesting spare parts suitable for reuse. Information sharing is critical to keeping products and materials in the product life cycle as long as possible [49]. Therefore, we introduce a DPP manager who is responsible for the creation and handling of DPPs.

Furthermore, the value network is modeled based on the assumption that all actors involved make their data available to the DPP and collectively contribute to a circular value proposition that strives for EEE lifetime extension. The decision-supporting data in the DPPs support the collection agent in assessing collected washing machines. The content of the DPP and a related data-driven process diagram are described in Chapter 5. We also introduce the business roles of repairer and spare parts supplier in our model to enable the lifetime extension of washing machines. The value addition of distribution in our model has no direct added value for our circular task and has, therefore, been ignored. In our model, we neglect materials recycling because it is at odds with our ambition of product lifetime extension.

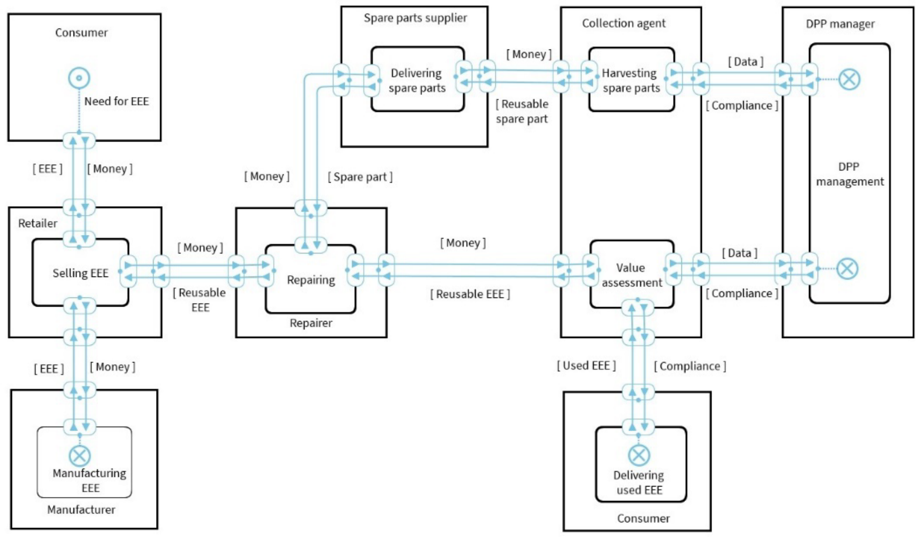

Figure 2. Proposed future e3-value model

The customer's need for a new or second-hand washing machine triggers the value network. In our model, We assume that manufacturers still produce new washing machines but that retailers, influenced by growing second-hand markets, sell second-hand washing machines in addition to new ones. The demand for second-hand washing machines requires a value network in which the value activities and the mutual value transfers between customers, retailers, repairers, spare parts suppliers, collection agents, and disposing consumers are economically attractive. Another possibility is that compliance directs actors to perform a value transaction, such as sharing and recording data in DPPs. The model shows that a DPP manager who takes care of DPP management supports the circular value activities of a collection agent. A cloud provider can execute the DPP manager's role. Furthermore, in our value model, harvested parts data are identified, registered, and recorded in the DPP. Although these data are valuable for spare parts providers and repairers when repairing collected washing machines, it falls outside the scope of our value model.

4 Field studies

As part of product lifetime extension assessment, the repairability of a washing machine largely determines the extent to which lifetime extension is possible [24]. Therefore, four semi-structured interviews with professional repairers provided insight into washing machines' product-specific factors that are decisive in assessing whether lifetime extension is possible. Repairers indicated that that most failure modes in non-functioning washing machines can be traced back to electronics, bearings, door, pump, pump filter, shock absorbers, carbon brushes, and foreign objects. According to the repairers, washing machines' bearing and electronics have a poor to moderate repairability. The repairability is strongly affected by diagnosis time, ease of disassembly, repairability time, and repair expertise [50]. Failure modes with a high repairability refer to the door, pump filter, inlet valves, heating element, shock absorbers, and foreign objects. The repairability of switches and the detergent system is moderate, according to respondent two. The general repairability score closely matches the findings of a washing machine study from a prior research [22], indicating that electronics and bearings generally have a low repair rate. Doors, pump filters, pumps, and foreign objects, on the other hand, have a high repair rate. Our research results indicated that failure modes with low repairability must be identified early in the assessment process. Product specification on manuals and repair websites provided insight into possible assessment factors related to product and performance specifications, such as fill weight, and energy consumption.

Collection agents instructed that a limited set of verifiable assessment criteria with a high predictive value should be verifiable in a limited time frame. Participatory observations at three collection agents in the Netherlands clarified that the current restrictions on access to data and brand-specific software applications to retrieve stored usage data in washing machines hamper automated, data-driven assessment. Therefore, only assessment criteria that can be tested pragmatically by an assessor are assessable in the current situation.

The initial elaboration resulted in 34 potential assessment criteria that assessors can use to determine whether lifetime extension is feasible. Structured observations at two collection agents in the first validation clarified that experts assess washing machines mainly on brand, visual condition, completeness, quality of bearings, age, and product type. Usage information was indirectly derived from visual inspections of washing machines. The lack of cross-brand standardization of the information on product labels hindered the understandability of product-specific information, such as product year and model number.

Desired assessment criteria, such as initial catalog price and year of construction, were also rejected due to the lack of data. The observations also revealed that the experts' scoring of the assessment criteria was affected by the availability of repair facilities and the harvesting of spare parts for reuse in repairable washing machines.

Furthermore, assessing washing machines depends highly on the expert's tacit knowledge, which hampered the objective selection of assessment criteria and their scoring.

During a second validation, a final simplified set of product and technical related assessment criteria was determined: washing machine type, brand, quality of bearings, and physical state (e.g., dents, rust, and completeness). The criteria are derivatives of direct assessment criteria that can be objectively tested upon access to the related specific data points. For example, according to the interviewed collection agents, the brand criterion indicates a washing machine's product and material quality, repairability, energy and water consumption, and expected market demand.

The assessment criteria are operationalized into data indicators. A distinction is made between primary and derived indicators. Primary data indicators prelude the data in a DPP and relate to the actual data values, such as energy and water consumption. On the other hand, derived data indicators often have a subjective nature, such as brand and the results of a manually performed bearing test. Suggestions have been made for possible information sources to verify the primary and derived data indicators. Acceptance standards were linked to the selected assessment criteria and related data indicators in coordination with collection agents and professional repairers. For example, a washing machine must be a German brand with functioning bearings.

Despite providing valuable indications about possible lifetime extension, the study revealed that the number of verifiable and the granularity of the selected assessment criteria and related data properties hinder objectified assessment in the current situation. Digital Product Passports potentially can eliminate these disadvantages.

5 Digital product passport and decision support

We conceptualized a DPP for washing machines to support decision-making across the EEE ecosystem during the product life cycle (see appendix A[2]). For this purpose, four use cases have been developed for EEE manufacturers, retailers, collection agents, and repairers to explore the practical relevance and content of the DPP. Due to the focus of this study on lifetime extension assessment, in this paper, we only present the use case of a collection agent. The use case was created based on ecosystem analysis (see chapter 3) and a semi-structured interview with a collection agent. Central to the use case is the business role change of collection agents from distribution and sorting centers to value assessment centers, where the pursuit of high-quality reuse options for collected washing machines is pivotal. As noted in chapter 3, this requires collection agents to be able to recognize and quantify the residual value of washing machines. Such a circular role for collection agents is only possible if they have sufficient information and data. DPPs support collection agents to perform the residual value assessment. Product information, technical information, product health, historical usage and repair information, and information about the expected ecological impact quantification

[2] All appendixes (A, B, and C) are openly available in: https://github.com/joni-moreira/dpp/tree/main/Stiksma_2024_Disposed_washing_machines

of lifetime extension are, among other things, necessary to arrive at an informed decision regarding lifetime extension.

In line with the conceptualization of the digital battery passport by Berger, Schöggl [9], our DPP consists of four information categories: (1) Washing machine product, (2) Value chain actors, (3) Status, diagnostics, and performance, and (4) Sustainability and circularity properties. The DPP differentiates into different information levels operationalized at the lowest level in data properties. When assessing returned washing machines, it is first essential to gain insight into the product characteristics as the foundation of the assessment process. Therefore, the first information category provides decision-makers with information on product identification, product support information, and product properties. The product identification of a washing machine refers to data properties such as the brand, the product type or model, the Global Trade Item Number, and the serial number. Identification of collected EEE enables value chain actors to access product data, such as product specifications and spare part numbers. The product support information refers to the documents that provide insight into the product features of a washing machine and support the technical repair process, such as failure diagnostics codes and product manuals. Product characteristics include specifications (e.g., washing machine type and load capacity) and performance. The performance category quantifies various performance indicators, such as energy and water consumption, noise level, and washing results.

The information category "value chain actors" provides transparency into value chain actors who have interacted with a device at any point during the product life cycle of a washing machine, e.g., during manufacture, sale, use, disposal, collection, or repair. The information on value chain actors covers general actor information, log data, and chain of custody. The general actor information contributes to the identification of involved value chain actors, their role in the value chain, their status, and their location. Log data refers to the collection and storage of data during the product life cycle of a washing machine. Such historical records provide actors insight into the data, status, and activities carried out by different value chain actors during a washing machine's lifecycle. This might include the production date, repairs performed, upgrades performed, error messages, transport movements, and the location of the collection point where a washing machine has been discarded. Information concerning the chain of custody clarifies the actor's responsibilities, e.g., regarding the physical washing machine itself and its sustainability and circularity performance (Berger et al., 2022). This information clarifies which value chain actor has been responsible for a washing machine product or part during a defined period.

The third information category "Status, diagnostics, and performance", is relevant for determining whether a washing machine can still be used for a potential second life phase after its disposal. This information category responds directly to the need for product and usage information to objectify whether extending the lifetime is feasible or not, based on technical parameters. Information on the washing machine's health, such as its physical condition, failure diagnostics, usage history, and residual lifetime is crucial. Information about maintenance history provides insight into the maintenance and repair activities that have taken place during a washing machine's product life cycle. The washing machine's performance may decrease during a life cycle. Information in the DPP therefore provides insight into the current performance of a washing machine, including its residual lifetime and energy and water consumption.

The fourth information category “Sustainability and circularity” are becoming relevant for value chain actors in a circular economy. Value chain actors are increasingly requested to objectify their sustainable and circular performance. Life cycle analysis methods and calculations play a significant role in the quantification of this information [51]. Information about sustainability-related properties in the conceptualized DPP provides insight into a product's environmental and social impact [9]. This environmental impact information relates to categories of impact, performance indicators, indicator calculation methods, inventory data, and impact assessment methods. The social impact can theoretically be operationalized in information related to working condition properties. The information on circularity-related properties relates to circularity performance and the product design-related properties of washing machines. Circularity performance can be operationalized in a similar way to information about sustainability properties. The underlying information refers to resource efficiency, materials used, increase in durability, and the useful lifetime of washing machines [9]. Circular performance assessments and provision for underlying information play a central role in this [52]. The information on the product design of washing machines provides insight into the applied circular product design strategy and the reparability of a product.

Appendix B shows a generic process diagram where DPP data support the lifetime extension assessment process. The following assumptions directed the design of the assessment process diagram:

i. Discarded washing machines are, to a large extent, still collected and assessed by collection agents.
ii. By 2030, a large part of collected washing machines will incorporate digital technologies such as Internet-of-Things, allowing insight into historical usage data and allocation of washing machines’ generated data to the cloud.
iii. All data in the DPP are assumed to be available and accessible by collection agents.
iv. The information systems in the EEE ecosystem are highly automated. Information sharing across EEE ecosystem actors is commonplace.
v. When designing the process diagram, it was assumed that the intake of washing machines and their lifetime extension assessment at a collection agent take place as a one-off assessment.
vi. Despite future digitalization initiatives in the EEE ecosystem, lifetime extension assessment also requires manual visual inspections, e.g., to assess the inside quality of a washing machine, to confirm previous data-driven diagnoses, and to identify root causes.
vii. Parallel to a data-driven assessment of washing machines and as part of a decision-support system, we assume that a decision support system (DSS) is available to check the data properties values in the DPP against acceptance standards. Due to the explorative character of the assessment process, the standards have not been defined yet and specification of the type and architecture of DSS fall outside our study's scope.

The assessment process tests in six steps whether the values in a DPP associated with an assessment criteria meet the standards in a DSS. In step 1, a collected washing machine arrives at a collection agent and is registered. By scanning a machine-readable optical label, the washing machine's identification data are extracted from the DPP. In step 2, the lifetime extension assessment of the washing machine starts. At the product level, a washing machine is assessed for generic factors. These generic factors relate to product characteristics, technical performance, market demand, and ecological impact. The assessment is based on the information in the DPP, whereupon data property values are compared to the standards in the DSS. If a washing machine does not meet these standards, it is not eligible for lifetime extension. In the case of acceptable values, the washing machine is diagnosed in step 3. This diagnosis focuses on the washing machine's status and health. During the diagnosis, the washing machine is assessed for physical condition, technical condition, product usage status, and maintenance and repair history. If the data properties values in the DPP are acceptable, a washing machine is visually inspected in step 4, such as completeness, rust, dents, and usage marks. This process step can be partially automated, for example, using photograph analysis. However, we assume, an internal inspection of the washing machine still requires a technical employee's involvement. In step 5, a final diagnosis of the washing machine is performed based on the assessment results in steps 3 and 4. In this diagnosis, the actual diagnosis based on the current status of the washing machine, as recorded in the DPP, is determined. Based on a 'diagnosis-recipe' approach, the DSS determines which possible repair activities must take place to extend a device's lifetime. Based on the estimated repair activities, the economic, technical, and ecological feasibility of extending the lifetime is tested in step 6. If this data-driven assessment meets the standards set in the DSS, the assessed washing machine qualifies for a lifetime extension. The feasibility test results in this process step are recorded in the DPP. If a washing machine is not eligible for lifetime extension, the DSS suggests whether parts or materials can be harvested from the washing machine.

As mentioned, during the assessment process, data are extracted from the DPP to determine the values related to specific assessment criteria. The required data for each assessment criterion refer to an information category, a specific sub-category, or a data property in the DPP. Appendix C provides insight into which data from the DPP is used for each phase in the assessment process. For instance, the professionalism of value chain actors is an assessment criterion, this criterion is part of process step 3 (device diagnostics). The assessment criterion, Environmental performance, is part of the general assessment in step 2 in which a washing machine is assessed for energy and water consumption. Economic feasibility criterion cannot be determined solely with the information in the DPP. Such information requires additional digital instruments and calculation methods aimed at objectifying the economic feasibility of washing machine lifetime extension, which is outside the scope of the DPP for washing machines.

6 Discussion

In previous chapters, we discussed how DPPs for washing machines support the lifetime extension by collection agents. Sharing, storage, and retrieval of DPP data in a digital ecosystem are critical for ensuring transparency, traceability, and accountability throughout a product's lifecycle. This facilitates compliance with regulatory standards, enhances consumer trust, and supports sustainable practices by providing detailed information on the origin, composition, and environmental impact of products. A notable ongoing initiative is the International Data Space (IDS), led by the International Data Spaces Association (IDSA). IDS aims to create a secure and trustworthy data ecosystem for data sharing and collaboration with emphasis on data sovereignty. The IDSA is a global network of organizations working together to develop and implement IDS. This initiative promotes decentralized architectures, standardized data models, and secure data exchange protocols to ensure data sovereignty, privacy, and trust. By adhering to these principles, the IDS framework enables seamless and controlled data sharing across various organizations, sectors, and countries.

In our prior work [53], we identified an open research direction while investigating the DPP implementation in the process of flow of materials in manufacturing. We identified the common gap on missing product data throughout this process if the data is from external partners in the value chain, which requires that appropriate interfaces for data exchange must be established, especially when it involves companies from different legislation areas (e.g., countries) and even competitors within the same country. IDS is highlighted as the most appropriate solution direction to address this problem, but the criticism from manufacturers still reflect a lack of business cases where all involved parts can improve their profits. We believe that, by leveraging on our value models presented in this paper, relevant business cases within the EEE ecosystem can strength the adoption of IDS-based solutions for integrating DPP systems. In this context, we believe that Environmental Management Systems can facilitate the widespread implementation of IDS-based DPPs, since this kind of system is specific designed to address some directives on research and policy-making in this domain, such as the Corporate Sustainability Reporting Directive (CSRD), established by the European Parliament to standardize sustainability reporting.

We have been collaborating with IDSA to address research needs related to IDS. Recently, we developed an IDS Connector Store [54], serving as a broker system to facilitate the discovery and selection of IDS Connectors, data sources, and participants (actors) active in a data space. This effort resulted in the definition of an IDS architecture that encompasses the primary IDS objectives, which is extensible for adding new elements within the IDS ecosystem, such as for the processes and actors covered by the DPP value models introduced in this paper. Therefore, a future venue for research is to exploit the relations between DPP and IDS actors, and how they can play overlapping roles, such as the DPP manager also playing the role of a data broker. This can represent a way to find optimized solutions, along with their service offerings, that allow all involved parties to improve their profits in future value exchange practices of manufacturing supply chains.

7 Conclusion

This paper addressed the current problem that data sharing in the EEE ecosystem is not commonplace. We introduced the DPP concept enabling data sharing across EEE ecosystem actors. Specifically, this paper explored how future DPPs have the potential to support collection agents to perform lifetime extension assessment for washing machines. We conceptualized the DPP and proposed a generic data-driven assessment process diagram that includes DPP data. Our contributions address several issues but are insufficient to overcome the described problem in full. For instance, though the role of a DPP and DSS has been explored in a generic data-driven assessment process, a practical demonstration is required. Moreover, digital technologies in washing machines enable continuous monitoring requiring a dynamic character of DPPs. However, how additional dynamic properties should be defined in the DPP for washing machines remains a topic for future research. Furthermore, our results are based on an analysis of one specific sector, the washing machine market. Our assumption that the data in the DPP for washing machines are accessible and available for collection agents depends on its adoption by the EEE sector and final legislation and regulations to reinforce this. Such adoption depends on the economic attractiveness of the value transactions between EEE ecosystem actors. For this purpose, future research also focuses on quantifying the proposed future e3-value model in various market scenarios to test the sensitivity of the value network to different market conditions. Nevertheless, we believe that our contributions and results can inspire extensions and generalizations beyond the mentioned issues and specific sector of washing machines.

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