Digital circular ecosystems: A data governance approach

Strategic product data management fosters circular ecosystems that reduce carbon emissions and resource consumption. To this end, legal frameworks are needed to set standards for systematic product transparency and interoperable tracking of materials. Analyzing the EU's Digital Product Passport (DPP), we propose the creation of publicly coordinated product data platforms to complement DPPs.

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Abstract
The growing research interest in digital product passports (DPP) and circular economy platforms portends an ecological economic transformation that will require improved strategic product data governance. Using the literature, we explore the technical and policy frameworks required by data-based policy instruments for digital circular ecosystems (e.g., DPPs). We analyze five empirical product life cycle cases to better understand how the strategic governance of product-related data can connect materials and product flows to shape new collaborative circular ecosystems. For this purpose, we provide new governance proposals for modifying European DPPs to enable the systematic tracking of materials.

Keywords
circular economy, data governance, platform, regulation, sustainability

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Over the past decade, EU regulators have recognized data as a strategic resource. Hence, we now have a European data law (Streinz 2021), which addresses the strategic role of information. Policy instruments (e.g., mandatory data-sharing and interoperability obligations) are developed to tackle the asymmetric information power of "Big Tech" (Brown 2020). Unfortunately, scant public attention has been paid to data regulations in the context of sustainability transformations. Hence, the European Commission is deploying data governance policies to stimulate the desired ecological transformation. The Digital Product Passport (DPP) is a relevant example. The general idea is that manufacturers should make important product-related data digitally available so that stakeholders can reuse the knowledge and materials involved (Adisorn et al. 2021).

The circular economy approach also highlights the role of data governance in the ecological transformation of the economy. Circular economy scholars tend to view it as a policy tool for supporting circular ecosystems, monitoring ecological costs, and increasing material efficiency throughout product life cycles (Berg and Wilts 2019, Hedberg and Šipka 2021, Kristoffersen et al. 2021). However, there is no current agreement on the specifics of the product data required or on how they should be collected and curated. Instead, 76 projects are under way to provide competing EU DPP formats (Jansen et al. 2022, p. 12).

This paper explores the data governance requirements of a circular economy and specifies the technical and policy requirements for product data sharing. We draw on recent literature in the field of information systems and data-based collaboration (Lis and Otto 2020, de Prieëlle et al. 2022) to support our central argument that policy interventions (e.g., DPPs) must be accompanied by comprehensive data governance policies (Piétron et al. 2022). That is, precise rules for generating, storing, accessing, and using product-related information are needed to support circular ecosystems and ultimately empower stakeholders to close material cycles and promote longer product lifetimes.

We proceed with this task in three steps. First, we lay out the theoretical implications of digital circular ecosystems and distinguish centralized digital platforms from decentralized DPPs. Second, we develop a data governance analysis framework and apply it to five exemplary cases of digital circular ecosystems.

Third, we analyze the data governance structure of the EU's DPP proposal and examine the technical and policy gaps that need to be filled to implement a data-based collaboration framework that will support circular ecosystems.

Concept of digital circular ecosystems

In recent years, the circular economy paradigm has gained popularity among policymakers, business leaders, and researchers as a pillar of sustainable society. In contrast to the orthodox "take–make–dispose" logic of value creation and destruction, a circular economy is a system in which value is created using existing products and materials across multiple-use cycles (Blomsma and Brennan 2017, Hofmann 2019). The assumption is that a circular economy will ease the anthropogenic pressure on nature by closing material cycles, extending product lifetimes, and dematerializing value propositions.

The concept of circular "ecosystems" is essential to understanding and pursuing sustainable production and consumption modes (Hofmann and Jaeger-Erben 2020). It is an essential characteristic of ecosystems that they produce system-level outcomes that are greater than the individual contributions of the constituent parts (Aarikka-Stenroos et al. 2021). This approach captures the configurations of actors, technologies, and institutions that cooperate through loosely coupled interdependencies and coevolutionary patterns (Thomas and Autio 2020). Actors from different industries interact at all five stages of the product life cycle (Hansen and Revellio 2020):

- ***Design.*** Product designers develop durable products whose modular designs permit low-emission, resource-efficient production and use, and easy repair and recycling.
- ***Production.*** Manufacturers ensure low-emission production of modular, durable, repairable, and upgradable products, by using renewable energy and recycled materials.
- ***Usage.*** Service providers enable collective usage and shared consumption of product-as-a-service systems to increase efficiency of products.
- ***Second life.*** Repairers and remanufacturers extend product life through maintenance and repair, refurbishment and resale, and reassembly with new components as required.
- ***Recycling.*** Recycling industries track and separate material flows to avoid waste and generate secondary raw materials.

Various factors hinder the institutional shift to a circular economy, for example lack of economic incentives, low raw material prices, technical path dependencies, and rapid innovation cycles. However, for inter-organizational cooperation in a circular ecosystem, communication and information deficits are major obstacles that lead to uncertainty and unstable relationships. As Berg and Wilts (2019, p. 4) stated, "the circular economy's implementation is primarily a problem of information". Echoing the information-oriented explanations of social structures from institutional economics (Williamson 1981) and economic sociology (Beckert 2009, pp. 259 ff.), scholars have identified informational problems that hamper the transformation to a circular economy (Berg and Wilts 2019, Hedberg and Šipka 2021, Jäger-Roschko and Petersen 2022). First, deficient information flows for secondary materials and used products (e.g., quantity, quality, and value) lead to high search costs. Second, the externalization of the ecological costs of new products leads to unjustified price disadvantages for used products and secondary materials. Third, information deficits prevent repair, remanufacturing, and recycling, often due to intellectual property rights. Fourth, the shared consumption of goods and services is hampered by a lack of trust and connectivity.

Consequently, various actors seek to employ the latest information and communication technologies to create *digital circular ecosystems* that may be centralized or decentralized. On one hand, existing circular ecosystems tend to be orchestrated by a central actor functioning as the information broker to reduce transaction costs (Paquin and Howard-Grenville 2013). In recent years, digital platform technologies have been employed in many circular ecosystems to establish centralized multi-sided online marketplaces (Blackburn et al. forthcoming). We conceptualize these as *circular ecosystem platforms* as their algorithmic infrastructures centralize information flows to facilitate the reuse of products and materials, thus reducing the overall consumption of resources. Examples include platforms for exchanging used products, components, and secondary raw materials (e.g., eBay or Cirplus), building collaborative open-source communities (e.g., GitHub), sharing product repairing information (e.g., iFixit), and accessing shared services and infrastructures (e.g., mobility-as-a-service platforms).

DPPs, on the other hand, can be regarded as components of a decentralized data infrastructure that enables the exchange of product-related data without a central information broker. As envisaged by the European Commission (EC 2022, p. 9), a DPP should "electronically register, process, and share product-related information amongst supply chain businesses, authorities and consumers". Hence, DPPs require a unified and harmonized data standard that allows the functional interoperability of heterogeneous information systems for sharing product data among various companies and sectors (Brown 2020).

Data governance for circular ecosystems

Technically, digital circular ecosystems – whether centralized or decentralized – must perform two basic functions. First, they must provide reliable information about the characteristics, quality, and components of products. Second, they must facilitate standardized data flows among independent actors to maximize value generation. Both functions are addressed by the research field of data governance (Khatri and Brown 2010). Essentially, data governance encompasses decision-making rights and rules about the collection, storage, processing, and sharing of data within and between organizations (Abraham et al. 2019). According- >

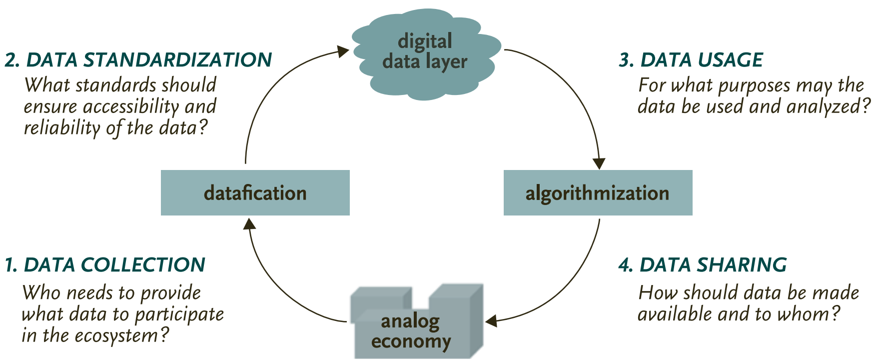

FIGURE 1: Data value chain: data collection generally represents the "beginning" of strategic data governance, with data sharing in the fourth stage, situated closer to the end of data-based value creation. Although this analytical chronology offers practical advantages, data governance is, in fact, recursive.

ingly, effective collaboration and risk mitigation requires clear rules about which stakeholder provides what data, how the data will be processed, and who will have access (de Prieëlle et al. 2020). To this end, the "data value chain" (Curry 2016) is a common analytical framework for multi-stakeholder information system governance. For circular ecosystem data governance we propose the following steps: *data collection, standardization, usage,* and *sharing* (figure 1).

In the following subsections, we apply our data governance perspective to five examples. We analyze digital circular ecosystems along the product life cycle, paying particular attention to governance mechanisms that specify how data are collected, standardized, analyzed, and shared. The cases were selected for their ability to demonstrate the potential of digital circular ecosystems based on product data from all five product life cycle stages. Owing to the great heterogeneity of projects from different sectors and groups of actors, their data management commonalities can be analyzed in more detail. Here, we employed a qualitative analysis of strategy papers, policy documents, and selected academic and think-tank studies.

Design: Three-dimensional computer-assisted design modeling of replacement parts to prolong product lifetime

The EU *FIWARE-enabled Service for Spare Parts Logistics in 3D Printing Digital Supply Chains (FIL3D)* project has demonstrated how a circular ecosystem can employ data from the product design phase (González-Varona et al. 2020). It focuses on manufacturers' three-dimensional (3D) computer-assisted design (CAD) datasets, which provide information about materials, tolerances, colors, and production specifications. CAD models serve as templates for 3D printing (i.e., additive manufacturing). Additive manufacturing can thus be used to repair broken producs and extend their life by producing spare parts on demand (González-Varona et al. 2020, p. 12). Using CAD data from a producer, consumers can generate replacement parts printed at a local 3D printing hub to be installed at a repair shop. The *FIL3D* project implements a digital platform to gather CAD data from manufacturers, offer them to consumers, and handle payments. To protect intellectual property rights, data access is limited to certified printers who forward the printed part to the consumer (González-Varona et al. 2020, p. 8).

Production: Life cycle inventory data make ecological costs transparent

Life cycle inventory (LCI) data can be used to assess the amount of greenhouse gas emissions during each phase of the product life cycle – from resource extraction to disposal (Suh and Huppes 2005). In the *Catena-X* business-to-business network, German manufacturers and software companies build life cycle inventory data exchange infrastructures to improve the ecological cost transparency of precursors (Capgemini 2021). Each company along the value chain is required to estimate its carbon dioxide equivalents per unit, add theirs to those of its suppliers, and pass the aggregated figures on to the next company in the chain. Given that car manufacturing, for example, involves up to 10,000 individual parts from more than 1,000 suppliers, an automated solution is needed. The German software company SAP has developed a new application to connect the enterprise resource planning (ERP) systems of companies along value chains to automatically monitor carbon dioxide emissions. Doing so provides comprehensive footprint calculations that reflect the actual environmental costs of (pre-)products, which can be used to monitor the environmental performance of companies (Reichel and Seeberg 2011).

Usage: Product status data promote sharing and maintenance

Status data tracking of product location, condition, and availability during the usage phase can enable shared consumption, thus increasing material efficiency as exemplified by sharing platforms (Konietzko et al. 2019). However, most sharing platforms lack interoperability, which impedes easy access and connected offerings. In 2018, the Finnish government introduced a data regulation mandating private and public mobility service providers to ensure the interoperable exchange of vehicle status and booking data. Following the principle of interoperability, a ticket for Mobility Provider B can be purchased via Provider A (Pursiainen 2019). Thus, the government aims to increase the accessibility and utility of intermodal (i.e., cross-company) shared mobility services. A similar capability is needed in the field of product maintenance to realize the full potential of a decentralized data-based maintenance ecosystem that includes distributed third-party repairers and remanufacturers (Bressanelli et al. 2018).

TABLE 1: Data governance analysis of five digital circular ecosystems along the product life cycle.

	DATA COLLECTION	DATA STANDARDIZATION	DATA USAGE	DATA SHARING
DESIGN	Producers create *digital three-dimensional (3D) computer-assisted design (CAD) models* of parts during product development.	Intermediaries provide different CAD data standards to enable broad applications that remain independent of suppliers.	Users access 3D model data to print parts with a local 3D printer.	Producers share 3D models via trusted intermediaries that protect intellectual property rights.
PRODUCTION	Producers create *life cycle inventory (LCI) data* for products to track material inputs and ecological footprint.	Companies agree on basic LCI standards to ensure functionality and comparability, software companies agree on common data formats for exchanging LCI data.	Producers and regulators use aggregated LCI data of products to optimize control of ecological performance.	Producers share LCI data via business software.
USAGE	Products generate *status data* about their location, condition, availability, energy consumption, and emissions.	Individual service companies develop data standards to improve the interoperability of shared services and comprehensibility of defective products.	Users easily access shared products, monitor product quality, and profit from an open repair ecosystem.	The sharing of product status data creates an integrated product service system accessible by consumers and repairers.
SECOND LIFE	Producers provide *repair and maintenance information (RMI)* for products.	Individual service companies develop data standards to enhance repairability.	Repairers use RMI data to facilitate product recovery and extend product life.	Producers share RMI data to facilitate product recovery and extend product life.
RECYCLING	Producers create *bill of material (BOM)* data declaring recyclable materials and components.	Individual service companies develop data standards to improve reusability and recyclability.	Recyclers use BOM data to disassemble complex products and facilitate collaborative resource recovery.	Producers share BOM data with recyclers and online marketplaces for secondary raw material.

Second life: Repair and maintenance information data extend life cycles

Repairing complex products such as cars or computers requires extensive knowledge of design and functionality as well as manufacturer-specific error codes. The provision and sharing of repair and maintenance information (RMI) are expected to open up a market for independent (local) repairers, creating a positive environmental impact by extending product life. The EU's vehicle emissions regulation of 2007 (Regulation EC 715/2007) obliges car manufacturers to grant independent repairers unrestricted access to repair and maintenance information data. Article 6 of the *Regulation EC 715/2007* states in general terms that repair and maintenance information data should be made available "through websites using a standardised format [...] and in a manner which is non-discriminatory compared to the provision given or access granted to authorized dealers and repairers". An evaluation by the European Commission in 2016 concluded that this regulation was partially successful. However, owing to the vagueness of specifications for data standardization and provision, car manufacturers tended to make repair and maintenance information data available only to a small group of authorized repairers or to share incompatible formats that prevented third-party repair (EC 2016, p. 9).

Recycling: Bill of materials data facilitate the recovery of raw materials

When a product reaches its end of life and is unrepairable, information about its composition, toxicity, and recycling potential can greatly simplify its recovery and disposal. An example is found in the construction sector, where the Dutch Madaster company provides a digital infrastructure for material passports to track and segregate reusable building materials. For each building, Madaster generates bill of materials (BOM) data that include quantities, chemical compositions, and features of each element to facilitate separation and sorting for later reuse (Burnley 2007). These passports are stored on a central digital platform, allowing users to perform data operations, such as calculating, and sharing. Hence, users can publish product data in online marketplaces to enable collection directly from the site.

From these five examples, we can identify four key commonalities of working heterogeneous data governance models: 1. they help generate or collect specific datasets containing specific product-related data, 2. they employ standardized data formats to ensure interoperability and broad use of the data, 3. they specify the communication channels used to share product data, and 4. they legitimize product data dissemination with the aim of recovering or reusing materials. These results are summarized in table 1.

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Data governance as a policy instrument

The academic discussion on DPPs has only just begun, and many competing standardization processes are in development (Adisorn et al. 2021, p. 2). Hence, many questions about DPP design and implementation remain unresolved. This is reflected in the EU's *Ecodesign for Sustainable Products Regulation (ESPR)* proposal (EC 2022),[1] which explicitly empowers the European Commission to adopt further delegated acts (EC 2022, Article 4) and encourage industry-led initiatives (EC 2022, Article 18) to complement regulation. In the following subsections, we analyze the EU's DPP proposal from a data governance perspective and derive basic technical and political insights from the five case studies discussed above.

Mandatory data sharing

The EU aims to establish "rules for setting requirements on mandatory [...] disclosure of information to market actors along value chains" (EC 2020, p. 2). In particular, Article 7 of the *ESPR* (EC 2022) specifies what data producers are required to share, including information on performance, disassembly, recycling, disposal, repair, and maintenance. Only if these data are provided in a DPP can the product be placed in the European market (EC 2022, Article 8). However, the mandatory provision of data on materials is limited to substances of concern, which limits many applications of the DPP. Moreover, there is a general lack of clarity about the scope and quality of the required datasets, which leads to more confusion. Given that companies generally seek to keep their data private in order to exclusively leverage the value of the data (Martens 2018, p. 11), further clarification on mandatory data sharing from the European Commission is needed (on data access and sharing see also Gotsch et al. 2023, in this issue).

Data standardization

In Article 9 of the *ESPR* (EC 2022), the European Commission requires that DPPs "shall be based on open standards, developed with an inter-operable format". This interoperability requirement is vital to processing DPPs at scale using software from different producers. However, the *ESPR* does not specify sectoral data standards with harmonized technical vocabularies for data formats and collection methods. This dilemma is similar to the interoperability obligation of the 2018 *Finnish Transport Act,* in which market-based product data standardization proved difficult to apply to a competitive multi-stakeholder market environment. As Tirole (2020, p. 16) stated, to eliminate power asymmetries in standardization processes and include the interests of small businesses and non-governmental organizations, standardization processes must be coordinated by governments or neutral nonprofit bodies.

Data accessibility and protection

The draft *ESPR* currently proposes making product data accessible through a "data carrier" attached to the product, which would serve as a link between the product and the data stored online (EC 2022, Article 9). Data carriers are also to be made accessible through retailers (EC 2022, Article 9) and a central registry established by the European Commission that includes product and data carrier identification (EC 2022, Article 12). However, DPP product data must still be stored by manufacturers (EC 2022, Article 10). This decentralized approach may pose difficulties when seeking access to large volumes of product data. For example, the 2007 vehicle emissions regulation mandated automated product comparisons but was hampered by inconsistent online data provisioning (EC 2016, p. 9). As most successful digital circular ecosystems are based on centralized platforms, regulators should consider complementing DPPs with product data platforms, which are comparable to the *European Product Database for Energy Labeling (EPREL)* and the *Substances of Concern in the Products (SCIP) Database* of the European Chemicals Agency. Moreover, a centralized platform could act as a trusted intermediary to validate data and protect the intellectual property rights associated with sensitive product-related datasets with varying levels of openness and differentiated "data access regimes" (Martens 2018).

Conclusion

In this paper, we argued that the strategic governance of product data is key to designing circular ecosystems with low carbon emissions and minimizing resource waste. The more digital information that is made available on the design, ecological footprint, accessibility, repairability, and recyclability of products, the faster we achieve circular ecosystems. Based on an analysis of five empirical product life cycle cases, we illustrated a broad variety of data governance approaches and focused on their commonalities. Applying a data governance perspective to the EU's DPP proposal, we hold that the ambiguous technical specifications on data collection and data standards and the lack of comprehensive material tracking guidance may cause high coordination costs that will impede circular ecosystems. Therefore, we propose the creation of publicly coordinated product data platforms that complement DPPs by protecting intellectual property rights and improving data accessibility.

However, this approach has limitations. First, an economic transformation depends on various factors, such as economic incentives and political regulation; hence, the availability of data alone is probably insufficient (O'Rourke and Ringer 2015). Second, the digitization of product data is expected to increase the demand for new technologies and cloud services, possibly

1 For an overview on the *Sustainable Products Initiative* see *https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative_en*.

leading to overall increases in energy and resource consumption (Lange et al. 2020). Therefore, the growing ecological footprint of information and communication technologies must be accounted for and balanced against the opportunities offered by product data governance.

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