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Data needs for product life cycle decision-making

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Digital product passports for a circular economy: Data needs for product life cycle decision-making

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A B S T R A C T

Digital product passports have been proposed as a policy instrument to enable decision-making throughout product life cycles in favour of a circular economy. However, due to nascent conceptualisation and weak industrial embeddedness, the contents of such an instrument are a source of uncertainty. Situated in a mechatronics context, this multiple-case study explores the data needs for digital product passports. Extant research reveals seven data clusters: (1) usage and maintenance, (2) product identification, (3) products and materials, (4) guidelines and manuals, (5) supply chain and reverse logistics, (6) environmental data and (7) compliance. To contextualise these clusters, interviews with three original equipment manufacturers (OEMs) as well as their respective customers, service partners, suppliers and third-party recycling companies were conducted. Through a survey, each specific data point was assessed in terms of importance, availability and sensitivity. The findings show differentiating needs for data across these actors, yet the exchange of data and its supporting infrastructure for closing resource loops remain at low maturity. Consequently, policymakers are recommended to roll out digital product passports in gradual stages, while industrial managers should proactively reconfigure data flows to account for decision-making in a reverse supply chain. Future research is encouraged to explore the use of digital product passports for decision-making in other industries.

1. Introduction

Policy instruments are essential levers for sustainable production and consumption. As vehicles for promoting aspirational objectives, they directly or indirectly incentivise industries to comply with a shared trajectory towards sustainable development. In a European context, numerous instruments have been deployed, including extended producer responsibility (Subramanian et al., 2009), product environmental footprint (Pedersen and Remmen, 2022) and eco-design (MacDonald and She, 2015). Each instrument helps support a resource-effective and competitive economy in pursuit of climate neutrality by 2050, as outlined in the European Green Deal (European Commission, 2019). Under the Ecodesign for Sustainable Products Regulation, the most recent proposal concerns a digital product passport, which is expected to enable informed decision-making throughout product life cycles in support of a circular economy (European Commission, 2022).

The proposal represents a reaction to a widespread industrial challenge. Although economically viable circular business concepts are starting to appear, particularly in the consumer electronics industry, many manufacturing companies remain hesitant to fully engage in a circular transformation due to plethoric (Ayati et al., 2022), entangled and context-dependent barriers (Jensen et al., 2022). Rather than being solely forward-oriented, supply chains must also be reconfigured to support a reverse flow of products, whereby products and materials are circulated at their highest utility, i.e. preserving as much embedded value as possible following 'the power of the inner circle' principle (Ellen MacArthur Foundation, 2012). Doing so calls for new forms of collaboration across supply-chain actors. Such collaborative arrangements build upon an alignment of interests, as well as a continuous exchange of data and information (Calicchio Berardi and Peregrino de Brito, 2021). However, a gap persists between the need for additional data and insufficient data sharing routines (Serna-Guerrero et al., 2022), arguably due to dispersed data and limited data sharing channels (Jäger-Roschko and Petersen, 2022) – despite increased attention in the role of a smart and digitally-enabled circular economy (Rosa et al., 2020). Consequently, actors find themselves lacking the requisite data

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about product life cycles to effectively occupy a new role in a circular supply chain (Preston, 2012).

Digital product passports are expected to remedy this in the form of storage, allowing actors across the supply chain to insert and extract relevant product data and information. Despite increased attention, the industrial implications of a digital product passport are only just beginning to be explored; in the scientific discourse, the concept remains in its infancy. In the literature, focus is extensively directed towards the coherency and consistency of the policy instrument and its operational features to make it a valuable platform rather than an administrative burden (Götz et al., 2022). On that note, extant studies are concerned with proposing design options (Plociennik et al., 2022) and defining system requirements, including access control to protect intellectual property rights (Adisorn et al., 2021). To substantiate these arguments, further research on the contents of a digital product passport is needed (Adisorn et al., 2021; Berger et al., 2022; Götz et al., 2022). Data and information are likely to vary depending on the decision, use case and the actor who utilises it (Walden et al., 2021). Understanding these dynamics is expected to qualify subsequent discussions about system requirements and, ultimately, enable the industrial adoption of digital product passports. Consequently, this study addresses the following research question:

What are the critical decision points and data needs for actors in a circular supply chain to support product life cycle decision-making?

The remainder of the study is structured as follows. Section 2 outlines the critical decision points and data categories for a digital product passport, as evident in extant research. These two streams define a coding structure for the empirical data analysis. Section 3 describes the methodological and empirical foundation as well as the data collection and analysis methods. Section 4 presents the empirically identified data needs, which are then discussed further in Section 5. Section 6 provides concluding remarks.

2. Conceptual background

This section delineates the conceptual background and academic discourse of the pillars upon which this research builds. First, we set the scene by introducing the notion of a smart circular economy. Second, we present the changing roles and decision-making contexts imposed on critical actors by the circular transition. Third, we introduce the notion of a digital product passport as a key enabler for operationalising circular strategies, including its contents, as presented in extant studies. In combination, these pillars construct a coding structure, and thus an analytical lens, through which the study is approached.

2.1. Towards a smart circular economy

In the contemporary business landscape, many companies are chasing the potential for enhanced competitiveness from two transformative agendas: circular transformation and digital transformation (Ingemarsdotter et al., 2020). Despite having distinct value potentials, an increasing body of research connects the two agendas (Chauhan et al., 2022), often under the concept of a smart circular economy. Most dominantly, emerging digital technologies are capable of tracking and tracing products throughout their life cycle (Giovanardi et al., 2023), thus both enhancing supply-chain transparency and data generation in favour of a circular economy (Antikainen et al., 2018). Examples of this include the implementation of big data analytics for high-quality decision-making in pursuit of a circular economy (Awan et al., 2021; Bressanelli et al., 2018), the application of RFID tags to estimate the remaining lifetime of end-of-life products (Ondemir and Gupta, 2014) or the use of cyber-physical systems to cope with complex remanufacturing systems (Rejeb et al., 2022). While many of these consider unidirectional capabilities (i.e. digital technologies as enablers of a circular economy), others emphasise their synergetic effects, including the ability of a circular economy to enable digital transformation (Uhrenholt et al., 2022). Unlocking such synergetic effects enables companies to reconcile a forward-oriented and reverse supply chain through data-enabled decision-making (Pagoropoulos et al., 2017). Despite this increased attention, a research gap persists between the scientifically theorised potential and its industrial reality (Rosa et al., 2020), which prompts a characterisation of the smart circular economy as pre-paradigmatic (Kristoffersen et al., 2020; Pagoropoulos et al., 2017).

2.2. Decision-making contexts in a circular economy

In contrast to a linear economy, which builds upon a 'take-make-dispose' system, a circular economy seeks to rethink production and consumption patterns through the lens of slowing, closing and narrowing resource loops at the micro, *meso* and macro levels in favour of social equity, environmental benefits and economic prosperity (Kirchherr et al., 2017). In the academic discourse, such ambitions are often substantialised through the utilisation of 'R-strategies', such as the 3R-strategies (Reduce, Reuse, Recycle) (Ghisellini et al., 2016). Despite the variance in these frameworks, they are founded on a shared set of principles. First, companies should utilise their inner loops (Stahel, 2016) and strive to maintain functional value rather than recovering material value. Second, the multiple strategies are not mutually exclusive (Goyal et al., 2018); they are bound together by the principle of cascaded product and material flows. To circulate products at their highest utility, collaboration across the supply chain is considered a key enabler (Chen et al., 2017). Such activity is not necessarily limited to a dyadic relationship between two parties (e.g., a manufacturer and a supplier) but may unfold in a complex network of actors (Sudusinghe and Seuring, 2022), all of whom are assigned new roles since the supply chain is reversed and is no longer solely forward-oriented. Extant literature (e.g., Ellen MacArthur Foundation, 2012) highlights five groups of actors as being of particular relevance to the activities of forming a circular supply chain. Their roles and pertaining decision-making contexts are described in the following subsections and summarised in Table 1.

2.2.1. Customers

Whether they are end-users or OEMs, customers can no longer uphold a passive role in terms of slowing and closing material loops (González-Sánchez et al., 2020), as they are expected to rethink a series of activities to increase circularity. First, procurement criteria must be expanded to not solely rely on traditional performance measures by integrating environmental properties and commitment and corporate social sustainability as decisive factors for more sustainable procurement (Tseng and Chiu, 2013), Second, along the use phase, customers are

Table 1
Decision-making contexts for a circular economy across supply-chain actors. The dotted line indicates that recycling companies differ from other actors as their change of focus does not take its offset from a linear vantage point.

	Supplier	Manufacturer	Service provider	Customer	Third-party recycling company
Linear supply chain	Forward-oriented production of components	Forward-oriented production of products	Time-based maintenance	Traditional procurement measures and disposal at end-of-life	Retaining material value with less regard for irreversible loss
Circular supply chain	Remanufacture of components	Selecting and employing value-retention strategies at product level	Condition-based maintenance	Sustainable procurement, product lifetime extension, end-of-life trajectories	Retaining material value with reversible loss

expected to extend product lifetimes and, eventually, explore end-of-life trajectories for products and materials to be circulated at their highest utility (Hopkinson et al., 2018).

2.2.2. Service providers

From a circularity perspective, service providers have traditionally been responsible for prolonging product lifetimes through various maintenance and repair strategies, such as using spare parts to exchange defective components. Time-based maintenance has long been considered the most suitable strategy (Takata et al., 2004). However, with the purpose of providing more accurate service offers, condition-based maintenance has gained traction, according to which decisions are based on data from monitoring product conditions (Ahmad and Kamaruddin, 2012). Although such a change of approach is not a new phenomenon and was hardly sparked by the circular transition, it draws upon the distinction between resource-effectiveness and resource-efficiency that is frequently highlighted in the circular economy discourse. For instance, Bockholt et al. (2020) argue that resource-effectiveness is tied to the utilisation of residual value (e.g., by recovering functional or material value), while resource-efficiency refers to the incremental process improvements of such activities.

2.2.3. Manufacturers

Due to resource-intensive upstream activities, resource scarcity and increased focus on extended producer responsibility, manufacturing companies can no longer be solely concerned with a forward-oriented supply chain and logistics setup (Lüdeke-Freund et al., 2019). Instead, they must begin to decouple the consumption of virgin materials from business growth. In terms of closing resource loops, one essential measure relates to the development of product take-back systems, as well as capabilities to retain value at its highest utility (Geissdoerfer et al., 2017). Consequently, manufacturers must be able to select and employ suitable value-retention strategies at product level – assessing potential for products to be reused or remanufactured, or whether selected components or materials can be returned to suppliers or third-party recycling companies (Lopes de Sousa Jabbour et al., 2019).

2.2.4. Suppliers

Rather than solely seeking material input from virgin resources, suppliers can improve sustainable value creation by developing capabilities to remanufacture post-market components (Xiong et al., 2016). The advantages of doing so include the utilisation of material expertise and existing facilities. In the early stages of circular transition, suppliers may find remanufacturing less attractive than manufacturers. However, as manufacturers increasingly explore remanufacturing, suppliers become incentivised to follow suit, as they would financially benefit from remanufacturing their post-market components over the alternative scenario, in which manufacturers would remanufacture the suppliers' components and thus reduce revenue for the supplier (Huang and Wang, 2017).

2.2.5. Third-party recycling companies

Although some manufacturers and suppliers have facilities to recycle materials (e.g., to remelt aluminium), many have outsourced this activity to third-party recycling companies. As opposed to the other actors, recycling companies are born with a circular purpose, albeit one that is seen as a 'last resort' since only the material value is left to be retained (Bockholt et al., 2020). Nevertheless, recycling companies are also finding themselves in transition. Traditionally, the common understanding has been that 'all recycling is good recycling'. As such, these companies have been measured on the amounts of materials sent to recycling or the recovery rate (Graedel et al., 2011). Now, increasing attention is directed towards the utilisation and quality of recycling materials, and recycling companies are being encouraged to prepare materials for the highest utility on the market, thus conducting recycling with reversible loss of material properties whenever appropriate.

In sum, a variety of actors find themselves transitioning towards new roles. Although they are listed as having distinct intraorganisational responsibilities, significant value is to be found in interorganisational collaboration and increased exchange of data and information (Leising et al., 2018).

2.3. Digital product passports: sharing routines and data needs

The most frequently mentioned construct in supply-chain collaboration for circular objectives refers to sharing data and information with collaborative partners (Sudusinghe and Seuring, 2022). Such routines are increasingly enabled by the proliferation of digital technologies, which are considered key levers of a circular transition (Uhrenholt et al., 2022) since the potential of collecting and utilising data is continuously expanding (Pagoropoulos et al., 2017). Consequently, an increasing yet scant body of literature aims to develop and demonstrate repositories for data to be utilised by actors across the supply chain for circulating products. Such repositories are increasingly conceptualised under the premise of 'passports' to accommodate the individual characteristics of their affiliation to products or materials. Being connected to each individual product, digital product passports are expected to serve as vessels for data sharing, as supply-chain actors – ranging from suppliers to third-party recycling companies – may both utilise and insert data to support each other in transitioning towards a circular supply chain (Adisorn et al., 2021). Across the industry reports and the academic discourse, however, the contents of such a digital product passport remain unclear and warrant further investigation (Adisorn et al., 2021; Götz et al., 2022). In general, the purpose of a product passport is taking shape, but it remains vaguely defined, particularly around which types of data and information are relevant to support decision-making across the value chain. Few reports and studies (Adisorn et al., 2021; Berger et al., 2022; Danish Business Authority, 2021; European Commission, 2022; Götz et al., 2022) point towards relevant data in their attempts to conceptualise digital product passports. Through their synthesis, seven data categories appear, as visualised in Table 2: (1) usage and maintenance, (2) product identification, (3) products and materials, (4) guidelines and manuals, (5) supply chain and reverse logistics, (6) environmental data and (7) compliance.

The high variety of data clearly reflects the multitude of factors that affect decision-making in a circular supply chain. Although these reports and studies serve to materialise the notion of a digital product passport, they share the limitation of having little industrial embeddedness and

Table 2
Data categories for digital product passports, as presented in academic studies and reports.

Data category	Usage and maintenance	Product identification	Products and materials	Guidelines and manuals	Supply chain and reverse logistics	Environmental data	Compliance
(Adisorn et al., 2021)		✓	✓	✓			✓
(Berger et al., 2022)	✓	✓	✓	✓	✓	✓	✓
(European Commission, 2022)	✓		✓			✓	✓
(Götz et al., 2022)		✓	✓	✓	✓	✓	✓
(Danish Business Authority, 2021)	✓		✓			✓	

neglect multi-actor perspectives in terms of data needs. This leaves a gap, as these data needs are expected to differ across the supply chain. Further assessment of these studies reveals three elements of concern that underpin data needs and require further scrutinisation for the industrial adoption of digital product passports. First, perceived *importance* refers to the degree of criticality for decision-making (Berger et al., 2022). Second, *availability* of data has received attention, as companies already have vast amounts of data, but housed in dispersed data management systems (Jäger-Roschko and Petersen, 2022). Understanding the availability of data may affect the rollout of the policy instrument and elucidate the readiness of companies to implement digital product passports. Third, *sensitivity* of data is a cornerstone for operationalising digital product passports. While actors may have no objections to disclosing certain types of data to the general public, other types may be considered critical to the business and thus require digital product passports to contain multiple levels of access (Adisorn et al., 2021).

Synthesising this, the conceptualisation, and ultimately the implementation, of digital product passports is contingent on industrial insights into data needs. Despite the emerging scientific debate, how data needs differ among supply-chain actors remains understudied. Moreover, due to deficient industrial embeddedness in the debate, the nuances of the importance, availability and sensitivity of the respective data points remain absent. Together, these two gaps construct the scope of this study.

3. Research approach

In response to the argument from Kristoffersen et al. (2020) that the area of data-enabled circular supply chains finds itself in a pre-paradigmatic stage, and that studies on digital product passports are scant with little industrial embeddedness, this study is explorative in nature and builds upon a multiple case-study methodology as described by Yin (2009). This aims to further strengthen the conditions for theory-building (Eisenhardt and Graebner, 2007), as it enables researchers to both examine the studied phenomena within and across settings (Baxter and Jack, 2008). Table 3 visualises the research design of the study, including its sources of data collection.

3.1. Case selection

Three circular supply chains were selected as the empirical outset for the study, each of which consists of suppliers, the manufacturer itself as the focal company, service providers, customers and third-party recycling companies. Combined, they represent critical decision-making contexts throughout the life cycle of a specific product for which the digital product passport is intended. This selection rests on the rationale that if such a passport is to be utilised by several actors across a circular supply chain as a vessel for data and information sharing, then multi-actor perspectives are needed for the identification of its contents (i.e. the data and information needs).

The process towards this goal can be divided into two activities. The first step was to identify relevant manufacturing companies. For this, three selection criteria were defined: (1) the cases must all be actively engaged in circular transition and exploring the potential of end-of-life value retention; (2) the cases must produce products for which digital product passports are expected to become legally mandated; and (3) the cases should represent the same industry, as data needs and value retention opportunities are expected to differ across industries. Three manufacturing companies were identified, all of which are based in Denmark and are large producers of mechatronic products. Furthermore, from this point, manufacturers were utilised to contact

Table 3
Respondents for data collection. Asterisk (*) refers to a response by a colleague, and superscripted letters ([a,b,c]) refer to joint interviews.

Role	Area	ID	Phase 1 – interviews: Respondent	Phase 1 – interviews: Duration	Phase 2 – survey: Response
Customer	Heat, ventilation, air conditioning, control technology	C1	Global product manager	35	
	Water treatment	C2	Circularity expert	40	X
	Heat, ventilation, air conditioning, control technology	C3	Group sustainability manager	N/A	X*
		C3	Strategic sourcing specialist	25	X
Service provider	Third-party service partner	SP1	Chief executive officer	30	
	Third-party service partner	SP2	After market manager[a]	25	X
		SP2	Service technician[a]		X
	Internal service unit	SP3	Senior service technician	30	X
Manufacturer	Power conversion technology	M1	Project manager	30	X
		M1	Project manager	35	X
		M1	Engineering director	20	
		M1	Standardisation manager	35	
	Cooling and heating technology	M2	Post graduate	25	
		M2	Circular economy project director	30	
		M2	Senior project manager	25	X
		M2	Head of Quality	30	X
		M2	Complaint analyst	25	X
		M2	Engineering director	30	
	Water pump solutions	M3	Global circular economy lead	35	X
		M3	Sustainable manufacturing specialist[b]	40	X
		M3	Lead engineer[b]		X
		M3	Lead sustainability material specialist	35	X
		M3	Project manager	30	X
Supplier	Cast aluminium	S1	Senior EHS manager	20	X
	Stainless steel	S2	Supplier sustainability manager[c]	50	X
		S2	Senior environmental manager[c]		X
	Cast iron	S3	Metallurgist	45	X
Third-party recycling company	Metals, hazardous substances, plastics, electronics	R1	Waste specialist	25	X
		R1	Key account manager	30	
	Electronics and plastics	R2	Sales & market director	40	X
	Stainless steel	R3	Group sustainability officer	40	
			Total	14 h 20 m	$N = 22$ (71 %)

other actors. For example, key account managers were used to contact customers, while procurement managers were used to contact suppliers. Customers were selected based on their level of maturity in the circular transition, their attitude towards collaboration and their strategic importance. Suppliers were selected based on the criticality of components in terms of environmental footprint and economic value. Service providers and recycling companies were selected based on existing agreements and current collaborations with manufacturers. In sum, the study draws on two sampling techniques – convenience sampling and snowballing, as described by Taherdoost (2016) – to use present collaborative experiences as a vehicle for encouraging participation among external actors. Linkages between the actors are visualised in Table 4.

Notably, it is in relation to the manufacturers that the other actors enter a role as either supplier, customer, service provider or third-party recycling company. Acknowledging the interchangeable roles in a circular supply chain, where customers also become suppliers, and where recycling companies also become customers, it was decided for this study to refer to each actor according to its role in a forward-oriented supply chain for communicative purposes. Such empirical objectification enables coveted in-depth multi-actor perspectives on a scantly studied phenomenon that is contingent on several factors (e.g. industrial differences). Consequently, rather than pointing towards formal generalisability across industries, this study provides indicative results from a mechatronic industry to support further attempts to conceptualise digital product passports, thus aligning with Flyvbjerg (2006), who argues that such an approach has often paved the way for scientific progress and innovation.

3.2. Data collection and analysis

The sample of actors enables an in-depth and multi-perspective exploration of data utilisation in a digital product passport. Studying such a complex socio-technical phenomenon calls for a qualitative approach. Consequently, the data for this study were collected through two phases.

Phase 1: The objective of this phase was to identify the data needs of a digital product passport. Semi-structured interviews were conducted with 28 practitioners, whose expertise was considered key to securing a circular supply chain. Interviews were conducted online. All interviews were recorded and subsequently transcribed, and interviewees as well as involved companies were all anonymised. In terms of data analysis, a conventional content analysis was selected as described by Hsieh and Shannon (2005), as this study seeks to explore a phenomenon with scant theoretical foundation. For this, the seven data clusters identified from the literature review (see Table 2) were used to create a coding structure. Within this structure, thematic codes emerged from scouting for patterns throughout the transcriptions, revealing the empirically derived data needs for a digital product passport.

Phase 2: Subsequent to the interviews, a survey was sent out to all interviewees. This served a twofold purpose. The survey helped validate and qualify the findings from the interviews by presenting initial results from the mapping of data needs. Furthermore, practitioners were asked to assess each data point in terms of relevance to them (as either user or provider) on a five-point Likert scale based on three parameters: (1) How *important* is a given data point to the actor utilising it, from 'not important' to 'of utmost importance'; (2) How *available* is a given data point to the actor providing it, from 'does not exist and would be difficult to generate' to 'data exist and are available'?; and (3) How *sensitive* is a given data point to the actor sharing it, from 'not sensitive at all' to 'highly sensitive'? Notably, rather than including all data points in every decision-making context, only those considered relevant to the respective decision are included. Consequently, the data points were passed through pre-sorting, as reflected in the high levels of importance. However, their relative importance differs, and coupling this to availability and sensitivity is expected to nuance the findings and enable a prioritisation of data points (e.g., by indicating critical requirements). Based on this assessment, the data points were then clustered into four groups:

Out of scope data points have low availability and low importance. These are not considered relevant for a digital product passport.

Supportive data points have high availability and low importance. As such data are readily available for sharing but of mediocre importance relative to others, they could be considered for a digital product passport but are not as essential to early phases of the rollout.

Focused development data have low availability and high importance. These data are particularly valuable for a given decision-making context, but they require extensive work to generate and structure the data by the industrial actors.

Critical data have high availability and high importance. Such types of data are considered critical contents of a digital product passport, as they are both available (or need minimal structuring) and add value to decision-making in favour of a circular supply chain.

Subsequently, sensitivity is added as an analytical layer to highlight the need to integrate multiple levels of accessibility into digital product passports, thus building confidence among industrial actors to engage in interorganisational data-exchange activities. A grey-scale colour-coding is applied to indicate this level of sensitivity, as illustrated in Fig. 1:

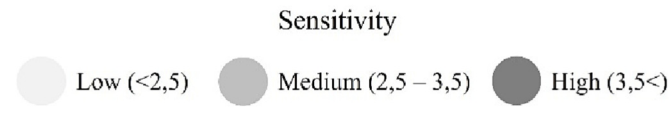

Fig. 1. Categories for assessing sensitivity.

4. Results

In this section, we present the empirical results. Here, it becomes evident that decision-making in favour of a circular economy builds upon two informative elements. First, several specific data points have been identified, including volume and recycled content. In other cases, a plurality of data points has been captured under a single category, such as labour conditions or environmental footprint. As an example, the latter covers a range of data points, such as carbon footprint, water consumption, land use change and ecotoxicity. However, such data points are combined into a single category to strike a balance between depth, breath and readability. Second, decision-making support is reliant on the availability of documents like product manuals, waste sorting guidelines and safety instructions. In the following subsections, the industrial needs for data and documents are connected to five use cases, as presented in Table 5. In doing so, we aim to concretise which types of data can support a circular supply chain while illustrating how they differ across various roles. Extending this mapping, we present results from assessing data needs in terms of their importance, availability and sensitivity.

Table 4
Linkages between the actors involved.

	Supplier	Manufacturer	Service provider	Customer	Third-party recycling company
Supply chain 1	S1	M1	SP1	C1, C3	R1
Supply chain 2		M2	SP2	C2	R1
Supply chain 3	S2, S3	M3	SP3		R1, R2, R3

Table 5
Cross-referencing identified data points and documents with use cases. (✓) refers to the actor who is expected to utilise the data, while (*) refers to the actor who is expected to provide the data.

	Customer: Sustainable procurement, product lifetime extension, end-of-life trajectories	Service provider: Condition-based maintenance	Manufacturer: Selecting and employing value-retention strategies at product level	Supplier: Remanufacture of components	Third-party recycling company: Retaining material value with reversible loss
Usage and maintenance					
Running hours and power (RH)		✓	✓*		
Location (LO)	*	✓	✓*		
External environment (EX)		✓*	✓*	✓	
Service log (SL)	*	✓*	✓		
Product identification					
Serial and product number (SN)		✓	✓*		
Manufacturing date (MD)		✓	✓*		
Country of origin (CO)	✓	✓	✓*		
Products and materials					
Bill of materials (BM)			✓*		
Number of life cycles (NL)	✓		✓*		
Volume (V)			✓*		
Material composition (MC)		✓	✓*	✓*	✓
List of hazardous substances (LH)		✓	✓*	✓*	✓
Recycled content (RC)	✓		✓*	✓*	
Compatibility of components across models (CC)			✓*		
Average lifetime expectance (AL)	✓	✓	✓*		
Availability of spare parts (AS)	✓	✓	*		
Guidelines and manuals					
Guidelines for non-destructive disassembly (GD)	✓	✓	✓*		✓
Product manual (PM)	✓		✓*		
Service manual (SM)	✓	✓	*		
Installation guideline (IG)	✓	✓	*		
Safety instructions (SI)	✓	✓	✓*		
Waste sorting guidelines (WG)	✓	✓	✓*		✓
Supply chain and reverse logistics					
Suppliers of components (SC)	✓		✓*		
Recycling partners (RP)		✓	✓*		
Customer return channels (CR)	✓		✓*		
Environmental impacts					
Environmental footprint (EF)	✓		✓*	*	
Compliance					
Product-specific regulation (RoHS/REACH) (PR)	✓		*		
Labour conditions (LC)	✓		*	*	

4.1. Customer: sustainable procurement, product lifetime extension and end-of-life trajectories

From a customer perspective, a digital product passport may serve a threefold purpose as a lever towards a circular supply chain. First, by increasing transparency across the supply chain, it is expected to support sustainable procurement in favour of all three dimensions of sustainability: social, environmental and financial. Doing so may support strategic targets for sustainable procurement and position customers more favourably for tenders, where sustainability is increasingly becoming a competitive parameter. To enable sustainable sourcing and procurement, a digital product passport is also expected to provide information about regulative compliance, for example, with regulation on labour conditions or with the RoHS Directive (Restriction of Hazardous Substances) and the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) Directive. Additionally, customers deem it a suitable platform for suppliers to disclose environmental data. This includes life cycle impacts across various parameters, such as carbon footprint and water consumption, or related circularity aspects (such as percentages of recycled content or number of product life cycles), all of which are considered highly important. However, generating and structuring such data demands attention from upstream actors; having knowledge about this enables the customer to select the most sustainable alternative.

Second, customers are essential to prolonging product lifetimes through continuous maintenance and repair, for example, by utilising their own service functions. For an elaborate description of adherent data needs, see Section 4.2, as the two specific decision-making contexts are closely related.

The third scenario for which a digital product passport is considered valuable for customers revolves around end-of-life options. When a given product no longer serves its original purpose, it must be treated safely, and its materials must be circulated at their highest utility. Channels for this may vary. If the product manufacturer operates a take-back programme, a passport could serve as a means of informing customers about return channels, such as directing them towards consolidated pick-up stations or pre-paid return boxes. If not, materials are likely to be recycled. Often, third-party recycling companies reward companies that disassemble and sort materials into clean fractions. Being able to access relevant documents, including guidelines for non-destructive disassembly as well as waste sorting instructions, would strengthen the ability of customers to handle electronic and mechanical waste responsibly.

The data needs to support all three of these decision-making contexts are combined in Fig. 2, which depicts the high demand for additional data from the customer perspective. Priority data include product compliance as well as guidelines, instructions and manuals, much of which are obtained already through procurement. While certain types of data related to slowing and closing resource loops exist (e.g., availability of spare parts or guidelines for non-destructive disassembly), a large share requires additional work from the product manufacturer, including in the fields of environmental footprint, customer return channels or tracking the number of life cycles.

4.2. Service provider: condition-based maintenance

Service providers, as represented in this study, consider a digital product passport a coveted platform for increased data sharing to strengthen their service offers and repair activities. At the same time, they expect to occupy a dual role as both users and providers of data and information due to their linkage position between manufacturers and customers. At its very core, as service providers instigate a maintenance task, they stand to benefit from easily accessing product identification measures, including serial and product numbers as well as country of origin and date of manufacture, to log the activity. When assessing the task at hand, knowledge about the external environment in which the product has operated is an essential determinant when it comes to inspecting the product to detect faulty components as well as taking proper safety precautions. For instance, if a mechatronic device has been operating in a marine environment, saltwater is likely to have corroded its metallic components, increasing the risk of defective parts over time. Understanding such conditions enables the service partner to deliver the most optimal service, for example, by applying substances to prevent saltwater corrosion onwards in the product life cycle. Alternatively, from a safety concern, it is vital for a service provider of pump solutions, for example, to know whether a pump has distributed water or chemical substances. Currently, obtaining such knowledge comes from experience and specialisation. As service providers are often highly specialised, they will in time accumulate knowledge about specific environmental conditions, yet with little attention to structuring such a body of knowledge. Due to its value, not only for service providers themselves, but also for manufacturers (see Section 4.3), the digital product passport could support formalising knowledge-sharing routines across supply-chain actors. Furthermore, as suggested by service providers, a passport would preferably provide data about the availability of spare parts and contain documents like a service manual and guidelines for non-destructive disassembly. In general, service partners see value in having all this information stored on a single platform. Therefore, they further suggest incorporating the service log into the digital product passport so that both they and the manufacturers can access the repair history of a product.

As shown in Fig. 3, priority data includes product identification measures and availability of spare parts, all of which hold low sensitivity. Furthermore, they cover a service manual and data related to materials (e.g., a list of hazardous substances and material composition), which hold higher degrees of sensitivity. Focused development data are characterised by more dynamic data, such as the service log, location and external environment, while installation guidelines are considered supportive data.

4.3. Manufacturer: selecting and employing value-retention strategies at product level

Manufacturers consider a digital product passport a promising vehicle for informing customers about potential channels for returning worn-out or defective products. This could involve either pointing to pre-paid envelopes or raising awareness about consolidated pick-up stations. When manufacturers have acquired products, they request extensive data about the use-phase of a product, as shown in Fig. 4. Practitioners deem digital product passports suitable for facilitating such data exchange. Key data and information include: When and where was the product installed, and how many hours has it been running? Has it operated at its highest capacity continuously or at different levels? Having knowledge about the running hours could – in combination with the estimated average product lifetime – provide an indicator of the remaining lifetime of a product. Moreover, gaining insight into

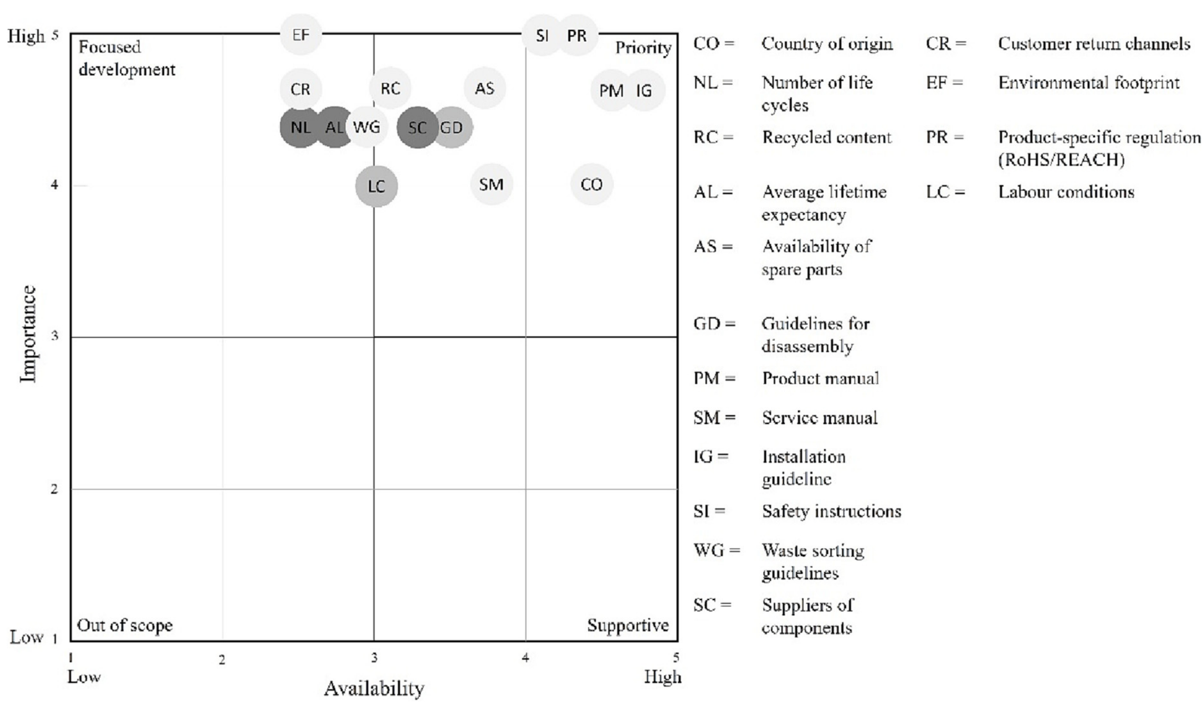

Fig. 2. Data to support customers in sustainable procurement, product lifetime extension and end-of-life trajectories.

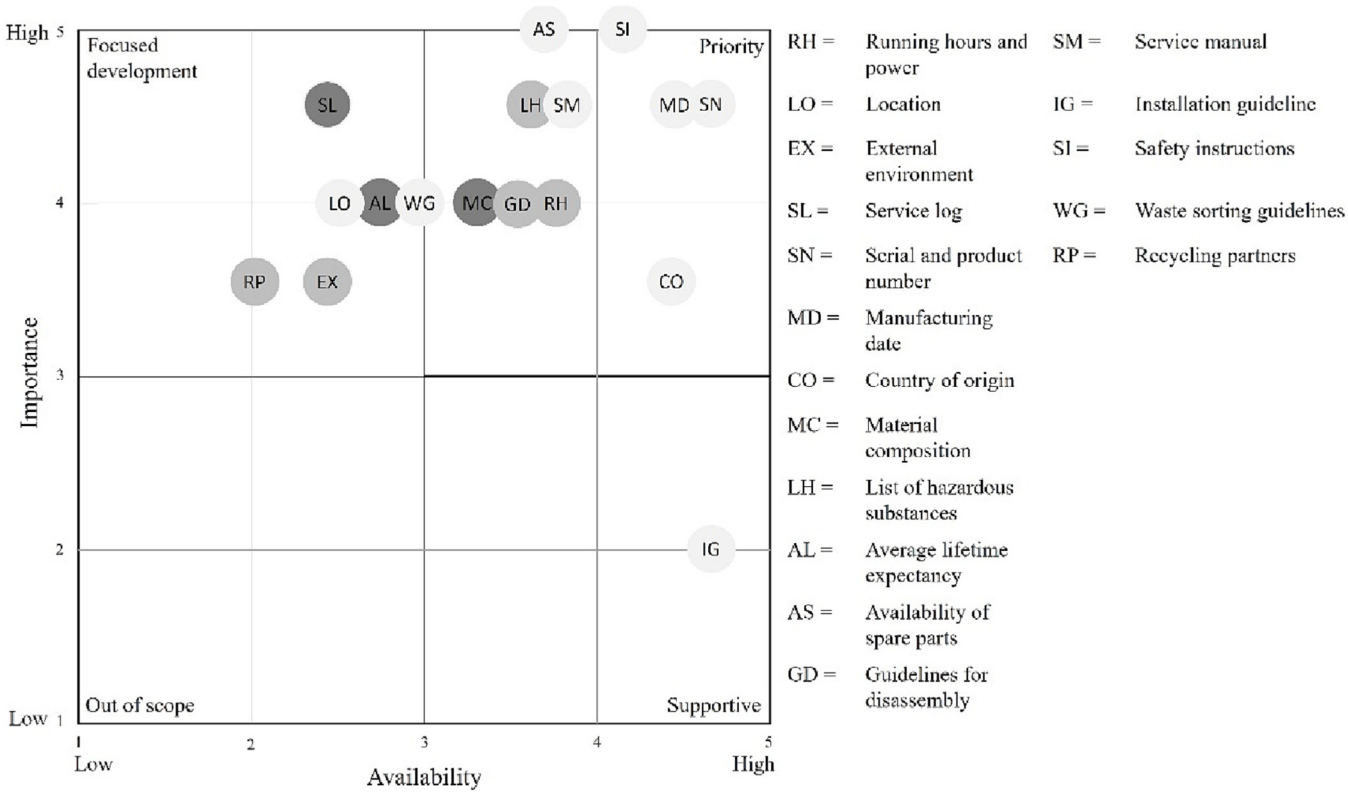

Fig. 3. Data to support service providers in conducting condition-based maintenance.

the external environmental conditions under which the product has been operating is considered essential to its ability to undergo multiple life cycles. Examples of harmful environmental factors include the amount of dust to which the product has been exposed, levels of vibration and contact with potential hazardous substances, which may have contaminated materials. Such use-phase data are considered core constituents of the assessment as to whether returned products can be reused or remanufactured or sent to a third-party recycling company.

As returned products are often either worn out or have failed on the market, direct reuse may not be preferable. Instead, manufacturers are inclined towards replacing worn-out or defective components, thus engaging in remanufacturing and refurbishing activities. Digital product passports are expected to enable this in multiple ways. Being able to access the service log, as updated by service providers or customers, to gain knowledge about the repair history is considered highly important to assess the lifetime of components, yet the availability of such data is rather

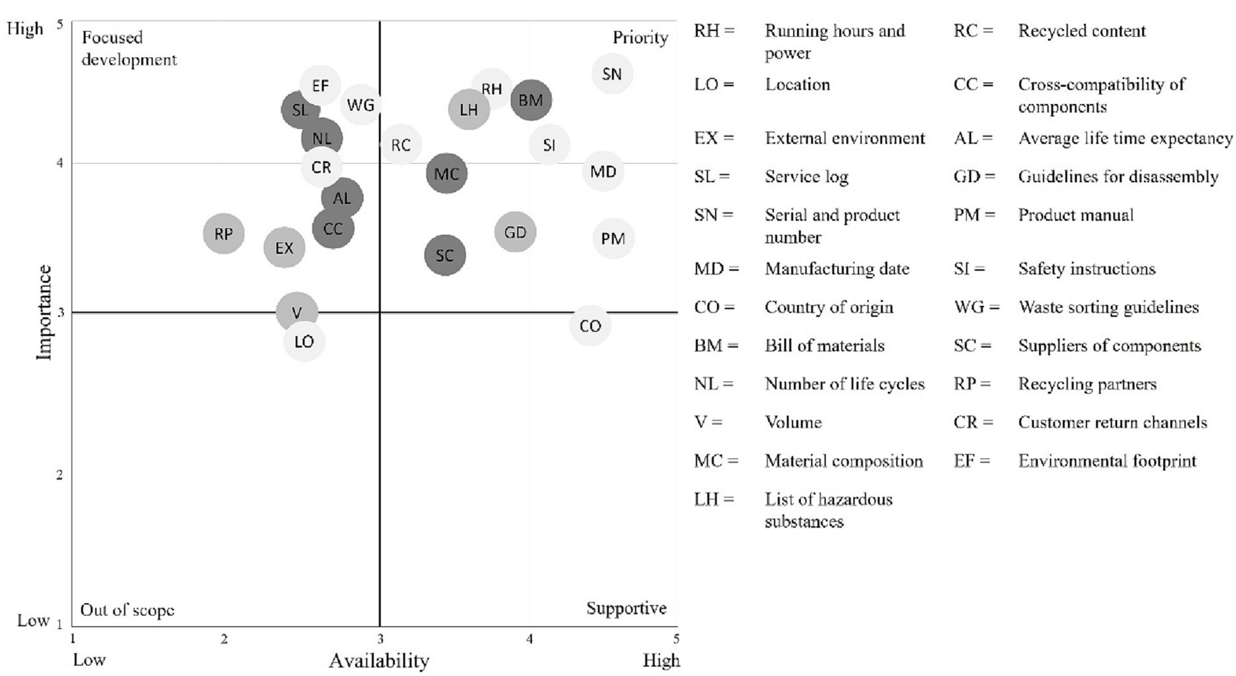

Fig. 4. Data to support manufacturers in selecting and employing value-retention strategies at product level.

low. As manufacturing companies are becoming increasingly aware of integrating circular design strategies (e.g., design-for-disassembly) into product design, adherent guidelines to secure non-destructive disassembly during remanufacturing or refurbishing could be stored and accessed in such a passport, which could not only feature a stepwise walkthrough but also highlight critical awareness points (e.g., when handling hazardous substances). In addition to the condition of components, which is particularly guided by use-phase data and thorough inspection procedures, the technical scope of remanufacturing and refurbishment projects is further reliant on environmental and financial parameters.

To support the decision to select components for a second life, manufacturers see value in using a digital product passport to access data about environmental life cycle impacts (e.g., carbon footprint) on both a product level and a component level. Combined with the financial value of a given component (e.g., through a bill of materials), this would enable manufacturers to target the components with the highest environmental and financial impact. Closely tied to this scoping process, remanufacturing activities – particularly in the case of long-life products – are also challenged by frequent design changes with little attention to the cross-model compatibility of components. Already now, but more so in upcoming product generations where circular principles are likely to become integrated into design, practitioners recommend that a digital product passport should contain information about the compatibility of components. This would add flexibility to the value retention options and partially remedy the challenges of foraging for post-market materials, as imposed by low product return rates. Finally, in cases where components or materials must be sent to suppliers or third-party recycling companies, respectively, a digital product passport is considered suitable for providing information about the actors involved in the production and circulation of a given product, thereby identifying subsequent trajectories in a cascaded flow of products.

Fig. 4 adds further detail to these findings. Aside from product identification measures, priority data include data of high sensitivity, which relates to product and materials (e.g., bill of materials, material composition and recycled content). Additionally, running hours and power, guidelines for non-destructive disassembly and a list of suppliers are considered of high priority. For manufacturers, significant effort is required to generate data and to inform about environmental footprint, availability of customer return channels and waste sorting guidelines, among others. Similarly, additional work is required to organise a service log. On the other hand, volume and location are considered out of scope, while country of origin is considered to be supportive data.

4.4. Supplier: remanufacture of components

Similar to product manufacturers, supplier engagement in closing resource loops is conditioned by reverse product and material flows, which provide new sourcing opportunities. Either components may be returned as an extension of the manufacturer's take-back programmes, or they are harvested from scrap vendors. In both cases, better access to high-quality data about a component (as facilitated by a digital product passport) is considered a key enabler for higher degrees of value utilisation. For example, rather than remelting – and thus recycling – aluminium and steel components, certain types of data may create fruitful conditions for exploring remanufacturing options. As exemplified by interviewees, such data could concern material composition, as well as a list of hazardous substances. Even in closed loops where any given supplier receives its own components, detailed insight into material composition is needed due to frequently occurring design changes and chemical thresholds, as induced by changing regulation. Related to this, suppliers consider a digital product passport a coveted platform for accessing data about recycled content. Although it is not considered essential, this could support suppliers in securing the quality and durability of remanufactured components, as well as tracking such content throughout multiple life cycles.

This is summarised in Fig. 5. While material composition and a list of hazardous substances are considered priority data, data about recycled content is categorised as supportive. Despite being frequently mentioned as a point of awareness by suppliers, the external environment is considered of little importance in this study, which is arguably caused by the robustness of their respective components (e.g., casted aluminium parts). Combined with low availability, external environment is categorised as out of scope in the decision-making context of suppliers.

4.5. Third-party recycling company: retaining material value with reversible losses

Mechanical recycling, as represented in this study, slightly differentiates itself from other activities as the trajectory for products and

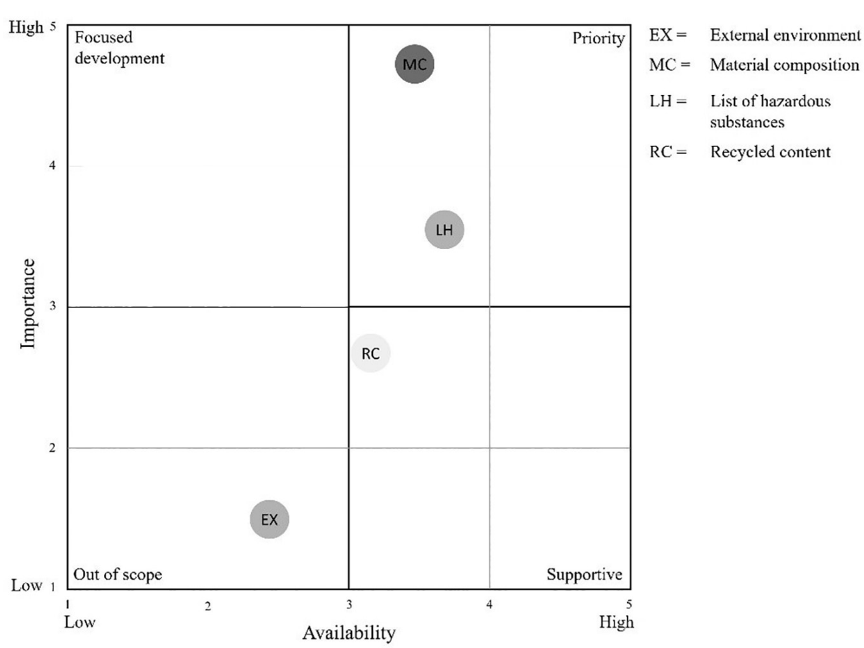

Fig. 5. Data to support suppliers in remanufacturing components.

materials is largely determined. However, within this scope, third-party recycling companies find themselves in continuous pursuit of increased quality of recycled materials. Access to certain types of data is expected to support such ambitions. Although pricing mechanisms incentivise manufacturers to sort materials into clean fractions, recycling companies often end up spending a significant amount of time disassembling products and sorting materials themselves before they are shredded. Being able to access disassembly guidelines and material composition in a digital product passport would enable recycling companies to generate even cleaner material fractions. In turn, this would improve the quality of the output, as increased transparency would enable the swift identification of hazardous substances (e.g., from batteries). The lack of data about material composition is a prevalent challenge for recycling companies, particularly in the case of plastics, where various types of plastics, chemical additives and fillers determine their recyclability in terms of reversible or irreversible property losses. Although plastic recycling symbols support this to a certain degree, they are rarely found on plastic components in complex products. To remedy this, data sheets are occasionally attached to the returned materials, yet without a detailed description of their compositions. As argued by practitioners, elaborating on such data sheets and integrating them into a digital product passport would provide coveted data exchange in a systematic manner, thus supporting more effective decision-making in the pursuit of high-quality recycling.

As shown in Fig. 6, data about material composition, a list of hazardous substances and guidelines for non-destructive disassembly are considered priority data, while waste sorting guidelines require additional work and are thus categorised as focused development data.

5. Discussion

Although the needs for data and information in a digital product passport have been scarcely studied in a systematic way, particularly from a multi-actor perspective, a few studies and reports from the academic and the grey literature point towards relevant data points to be included, albeit with only scant empirical foundation. As presented in Table 6, this section aims to juxtapose these suggestions with those presented in this study to highlight similarities and differences, thus both nuancing data points and aiding to materialise the frequently mentioned ones as essential contents of a digital product passport.

Compared to most extant reports and studies, this study identifies several data points, all of which are considered valuable to supply-chain actors as levers for the development of decision-making capabilities in a circular economy. This is likely to reflect the industrial embeddedness of the study, which is in contrast to Adisorn et al. (2021) and Berger et al. (2022). By situating the object of enquiry within a small-scale sample of a supply chain, in which actors are becoming increasingly attentive towards the circular transition, practical experiences with a lack of data and information become further augmented. The extant reports and studies depict a dispersed overview of the data and information required for a digital product passport. Frequently mentioned data include a list of hazardous substances, environmental footprint, material composition and product identification measures (Berger et al., 2022; Götz et al., 2022). Based on their perceived importance and partial availability, this study corroborates such findings but nuances them by situating data points in the decision-making contexts of multiple actors. A similar tendency is found in the case of guidelines for non-destructive disassembly, although the option of digitising existing guidelines and manuals has generally received little attention. In the existing studies and reports, data related to usage and maintenance are scantly mentioned, which may indicate a slight incline towards making digital product passports a static platform that captures relevant product data during upstream activities, as argued by Adisorn et al. (2021). However, this study finds that accessing data about running hours and power as well as the service log constitutes essential decision-making support for service providers and manufacturers to unlock inner looping strategies like repair or remanufacture, which may advocate for a more dynamic platform. In terms of a reverse flow of products, neglecting such data may result in a digital product passport that favours third-party recycling companies, as they heavily rely on data from upstream activities, rather than supporting the engagement of a broad array of actors as emphasised by the European Commission (2022) and Berger et al. (2022).

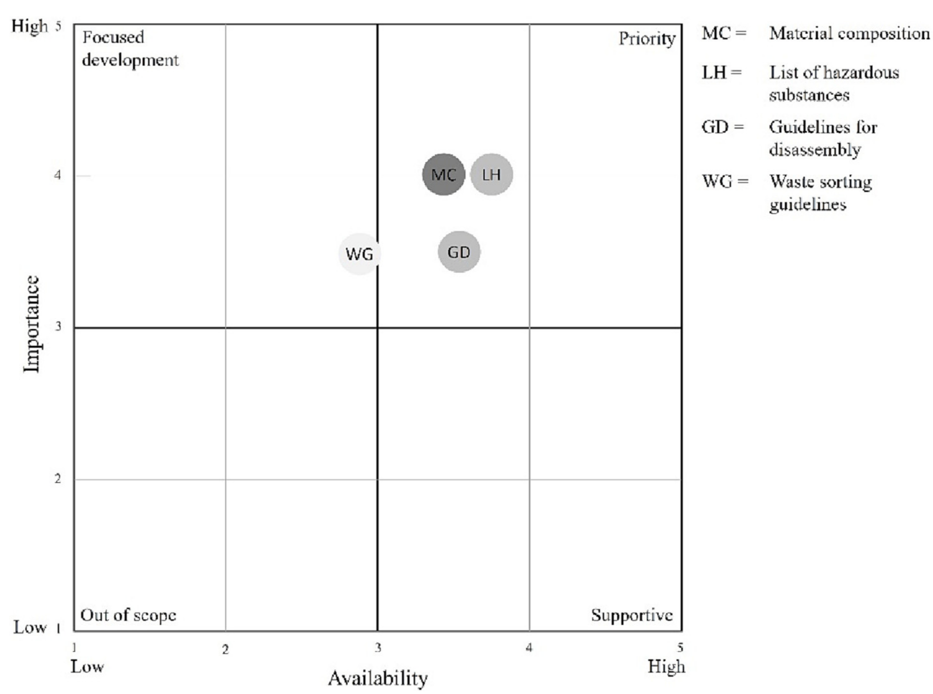

Fig. 6. Data to support third-party recycling companies in retaining material value with reversible losses.

Table 6
Comparing identified data points to extant studies and reports.

	Academic literature		Grey literature		
	(Adisorn et al., 2021)	(Berger et al., 2022)	(European Commission, 2022)	(Götz et al., 2022)	(Danish Business Authority, 2021)
Usage and maintenance					
Running hours and power		✓			✓
Location				✓	
External environment					
Service log		✓			✓
Product identification					
Serial and product number	✓	✓		✓	
Manufacturing date	✓	✓		✓	
Country of origin		✓		✓	✓
Products and materials					
Bill of materials		✓			✓
Number of life cycles					
Volume					
Material composition	✓	✓	✓	✓	
List of hazardous substances	✓	✓	✓	✓	✓
Recycled content		✓	✓		✓
Compatibility of components across models					
Availability of spare parts			✓		
Average lifetime expectancy		✓			✓
Guidelines and manuals					
Guidelines for non-destructive disassembly	✓	✓	✓	✓	
Product manual					
Service manual	✓				
Installation guideline					
Safety instructions					
Waste sorting guidelines	✓			✓	
Supply chain and reverse logistics					
Suppliers of components		✓		✓	
Recycling partners		✓			
Customer return channels					
Environmental impact					
Environmental footprint	✓	✓	✓	✓	✓
Compliance					
Product-specific regulation (RoHS/REACH)	✓		✓		
Labour conditions		✓		✓	

Examining data needs further reveals a pattern that the more open the decision-making process is i.e. more options under consideration, the more data does it rely upon. This is clearly illustrated in the juxtaposition of manufacturers and third-party recycling companies. In the case of product take-back, manufacturers inspect returns to make an assessment of the suitable value-retention strategy, either internally or externally, which is contingent on multiple factors, including the external environment and repair history, as also argued by Berger et al. (2022). By contrast, third-party recycling companies experience less uncertainty as the trajectory of materials is pre-determined, particularly in the case of mechanical recycling, as material fractions are shredded and thoroughly sorted afterwards. Consequently, only a few types of data would support recycling companies in conducting high-quality recycling.

5.1. Implications for policymakers

In order to ease industrial adoption, policymakers face the task of striking a balance between setting mandatory requirements for data in a digital product passport – and thus pushing for increased transparency – and protecting intellectual property rights and permitting actors to withhold critical data. This study supports policymakers in doing so through three findings. First, by exploring the data needs from a multi-actor perspective, this study finds that actors have differentiated needs depending on their positions in a circular supply chain. Highlighting such needs can assist the recently established working groups in defining mandatory data requirements to support decision-making throughout product life cycles. Second, the study confirms that certain types of data, such as material composition, bill of materials or number of life cycles, are considered fairly sensitive. Combining these two aspects calls for multiple levels of accessibility, tailored to the respective needs of each group of actors. This is further argued to increase the attractiveness of a digital product passport, as it removes the risk of data being misused, for example, by competitors. Third, another key consideration for policymakers refers to the rollout of digital product passports. This study contributes to this by examining the availability of data. While certain data (e.g., product identification measures and manuals) are readily available, data related to environmental performance and circularity require additional prioritisation. Therefore, this study corroborates the argument from Götz et al. (2022) that the implementation of digital product passports should be initiated at a small scale – with selected data needs and with flexibility for companies to iteratively develop and refine their data sharing capabilities.

5.2. Implications for industrial managers

From a resource-utilisation perspective, companies could benefit from rethinking data management in favour of a circular supply chain already now, and should thus start preparing themselves on certain aspects – at both a company level and a supply-chain level – for changing institutional settings. What is required, however, differs along the circular supply chain, and this study provides guidance to industrial managers as to how to prioritise their data management throughout product life cycles. Therefore, the findings act as a communicative vessel to enable companies to engage in discussions – within as well as beyond organisational boundaries – about how they can support each other in organising an appropriate data flow. In terms of upstream activities, suppliers and manufacturers are encouraged to assess the availability of relevant data (e.g., on material composition, recycled content or environmental footprint) and explore the possibility of digitising manuals and guidelines. These should be matched with current needs to detect gaps and thus identify starting points for further examination. Furthermore, manufacturers and service providers are encouraged to co-organise new routines of sharing the service log, which are found to benefit both parties. For data related to the use phase (e.g., external environmental conditions), a manufacturer argued that customers are unlikely to be aware of potentially hazardous environmental conditions. For a long-term solution on an industrial scale, manufacturers could consider integrating sensors to detect certain environmental conditions as well as tracking other types of use-phase data, such as running hours and power. Customers should not only request additional data, thus incentivising manufacturers to generate and share it, but preferably engage in updating service logs as well as reversing product flows by exploring end-of-life trajectories, including the availability of product take-back systems.

5.3. Theoretical contribution

Due to the novelty of the policy instrument, industry reports and the academic discourse share the objective of conceptualizing digital product passports in broad terms with little attention to the industrial implications. This study extends the current debate through two central contributions. First, we identify data needs for digital product passports, as suggested by Götz et al. (2022), and situate such needs within five industrial decision-making contexts. Second, we analyse the underlying aspects of importance, availability, and sensitivity for each respective data point to divide them into four groups, namely priority data, focused development data, supportive data, and out-of-scope data. For both contributions, we align with extant studies (e.g. Berger et al., 2022) on exploring data *needs* for a digital product passport rather than awaiting data *requirements* from regulatory bodies, yet we expand the scope by including perspectives from five groups of circular supply chain actors. By accentuating the differentiating needs for data, we further challenge the current academic discourse on digital product passports, which favours static upstream data for decision-making support over dynamic use-phase data. In terms of value retention, we argue that both are essential features for unlocking a cascaded product flow, thus both supporting the recovery of the functional value as well as the material value.

Furthermore, in a research field that is constantly in movement, the contributions construct a reference point to concretize – and ultimately advance – the discourse on data-driven decision-making for a circular economy on two particular areas of research. First, insights into the differentiated data needs are expected to enable further research on system requirements for digital product passports to substantialise, as a concretisation of coveted data qualifies subsequent discussions on interoperability and levels of access. Second, by studying the exchange of data and the utilisation hereof, as facilitated by a digital product passport, from a circular supply chain perspective, the findings offer guidance for improving intra- and interorganizational knowledge management, which are considered essential collaborative and coordinative building blocks towards a systemic transition (Farooque et al., 2019).

6. Conclusion

This study set out to explore the research question: *What are the critical decision points and data needs for actors in a circular supply chain to support product life cycle decision-making?*

In the pursuit of this, five decision-making contexts have been identified, each of which represents a core activity from an essential actor in a circular supply chain. In all cases, enhanced transparency and better access to high-quality data, as facilitated by a digital product passport, is considered valuable for product life cycle decision-making. More specifically, a total of 28 data points have been identified, clustered into seven categories: (1) usage and maintenance, (2) product identification, (3) product and materials, (4) guidelines and manuals, (5) supply chain and reverse logistics, (6) environmental data and (7) compliance. Linking these to the five decision-making contexts illustrates how data needs for utilising digital product passports differ along the circular supply chain. Subsequently, the data points are assessed in terms of their perceived importance, availability and sensitivity. This enables a categorisation of data points to support practitioners in strengthening their data management, while providing policymakers with industrial perspectives on the contents of digital product passports. Both are further validated by comparing the identified data points with extant studies and reports.

Reflecting on the scope of this study, certain limitations must be highlighted. Concerning the objective of exploring data needs for a circular supply chain, authorities were not included despite their important role in conducting market surveillance and securing coherence across policy instruments. Likewise, the presented data needs support circularity at the actor level; they do not monitor or improve sustainability at a higher level. Furthermore, this study is situated in the mechatronics industry. Data needs are likely to differ across industries, albeit with a share of similarities, which brings their generalisability into question.

As the scientific debate is only starting to take shape, several avenues for further research can be outlined. First, it is relevant to explore cross-industrial similarities and differences in terms of data needs. This would both elaborate on the findings from this study and materialise the contents of digital product passports. Second, it is yet to be assessed how the availability of digital product passports can support decision-making as part of a circular economy. Third, it is considered relevant to understand the driving mechanisms and potential challenges for industries to adopt digital product passports. Fourth, further research is suggested to explore system requirements by utilising the findings from this study to illuminate the areas of interoperability and data governance and the facilitation of multiple levels of access, including through the lens of blockchain technology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Interview guide for data collection

Theme	Question
Introduction	• What is your role at your company?
Digital product passports	• When hearing about this digital product passport, what are your immediate thoughts? • Do you believe that better access to data and information could strengthen the circular transition? ○ Why/why not? • In which situations do you believe that a digital product passport can support you?
Creating a scenario for a decision-making context that fits the role of the interviewee. The first question in the following is an example of a supplier:	
Needs for data and information	• Let us imagine that a product manufacturer receives a worn-out product from the market, disassembles it and sends a component to you to make it function again. Which types of data could support you to do so? • Who should provide this information? • To what extent does this already exist? • Are some types of data more important than other types of data?
Systems	• How important is it that a digital product passport can communicate with other systems? ○ Why? • Which systems should a digital product passport communicate with?
Outlook	• Do you feel that you are ready to explore and implement a digital product passport? • Do you see it as a valuable tool or an administrative burden? • Which drivers do you see towards implementing digital product passports? • Which barriers do you see to implementing digital product passports?

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