Impact Pathways: Digital Product Passport for embedding circularity in electronics supply chains

Abstract

Purpose – This impact pathways paper identifies drivers and barriers for digital product passport (DPP) applications in electronics supply chains and to derive future research pathways.

Methodology – 39 interviews were conducted with three Original Equipment Manufacturers (OEMs) and their suppliers, customers, recycling partners, DPP service providers and an international standards organisation.

Findings - The results show the four key drivers for DPP adoption: improved decision making to transition towards a circular economy, ensuring regulatory compliance, improving transparency across the supply chain, and enhancing customer engagement. Four main barriers exist: developing and communicating the business case for DPP adoption, increased need for data, data standards and ensuring interoperability between systems, the extent of implementation effort needed and ensuring data security and integrity.

Originality/value – This is one of the earliest papers to concisely summarise the main drivers and barriers of DPP adoption and present a comprehensive research agenda for operations and supply chain management.

Keywords Digital Product Passport, electronics supply chain, transparency, circular economy

1. Introduction

A Digital Product Passport (DPP) can be defined as a digital record of a product's lifecycle from source to end-of-life that contains product-related data with a predefined scope and agreed-upon data management and access rights. The data captured by the DPP are conveyed through a unique identifier, which is accessible via electronic means through a data carrier. Thus, the products must have a link to the product passport on the product itself. Such data can be dynamic and related to the product's history (e.g. product usage conditions, maintenance and repair history) and its environmental life cycle (e.g. energy consumption, water consumption, emissions) and static such as material datasheets, supplier certifications, disassembly instructions, and social due diligence certificates. The intended scope of the DPP is to facilitate the transition to circularity, value retention for reuse, remanufacturing, recycling, and regulatory compliance (Batista *et al.*, 2023; Langley *et al.*, 2023).

Let us consider an electronics equipment manufacturer that has a large variety of products with different sizes, weights, and material content. Such products contain precious metals such as copper, gold, silver, critical rare earth elements used for integrated circuits, magnets in small motors, hard drives, capacitors and plastics for multiple parts (CIRPASS, 2024). The company recognises that it has a significant environmental impact in terms of resource consumption, greenhouse gas emissions and electronic waste, which are all increasing due to the rapid growth in sales worldwide. The company must set ambitious targets and work towards achieving those. Indeed, electrical and electronic equipment is the fastest-growing waste stream in the EU, with annual growth rates of 3-5%. Europe produces the most e-waste per capita worldwide with around 11kg per person/year, but less than 50% of such waste is recycled in the EU, resulting in lost value in raw materials of €13 billion/year (Pwc, 2023).

Moreover, policy makers have acknowledged the importance of DPPs. In a recent proposal for Ecodesign for Sustainable Products Regulation (ESPR), the EU has explicitly mentioned DPPs as a means for product sustainability (European Union, 2022). DPPs are expected to provide information about regulatory compliance, for example, related to labour conditions or with the RoHS (Restriction of Hazardous Substances) Directive and the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) Directive (Jensen *et al.*, 2023). The global nature of supply chains and cross-border trade implies that DPPs need to serve the objectives of multiple regulatory regimes (King *et al.*, 2023).

Thus, the electronics equipment manufacturer must plan to adopt DPP across its supply chain, although the specific product groups or the reach covered by the regulation hasn't been finalised yet. The overarching goal of DPPs will be to address the lack of consistent and precise information flow about resources, products, and processes across the supply chain (Walden *et al.*, 2021). The data collected should facilitate decision making about choosing the optimal circular pathway for the product. DPPs can support a company's transition to CE and enable circular business models by helping to extend product lifecycles and by reducing the products' environmental footprint (Honic *et al.*, 2019). It has to ensure that the end-of-use (EoU) product is treated safely and that its materials are circulated at their highest utility, preferably retaining the functional use of individual parts and not just their material content (Jensen *et al.*, 2023). This not only requires a thorough assessment of the product attributes (e.g., material content, quality, source) but also of the sustainability performance and usage conditions at a product level throughout its usage and at the EoU. To achieve this, high-quality data is needed, which is often missing due to a lack of transparency across supply chains (Honic *et al.*, 2019; Kouhizadeh *et al.*, 2021).

Transparency is the extent to which information is easily accessible to partners and is fundamental for improving supply chain performance and sustainability (Adhi Santharm and Ramanathan, 2022). Traceability allows tracking products and providing information about their origin, production and distribution processes, at the point of use. There is extensive literature on how distributed ledger technologies (DLTs) can facilitate transparency and traceability across supply chains (Gligor *et al.*, 2022), while a few specifically analyse such applications for circular supply chains (Gong *et al.*, 2022). DPPs will require the deployment of DLTs to provide data across the product's lifecycle to enable decision making for its circularity. However, multiple barriers and uncertainties remain regarding DPP adoption, which are different from DLT adoption in supply chains primarily due to data collection over a product's lifecycle and regulatory mandates. Research on DPPs is at a nascent stage (Langley *et al.*, 2023)Hence, this is the opportune time to engage in academic research to support firms across the supply chain, inform policy makers, and identify research pathways.

The successful introduction of DPPs will require the identification of the data that need to be captured related to usage and maintenance, product identification, materials, guidelines and manuals, supply chain and reverse logistics, environmental, and compliance (Jensen et al., 2023). Supply chain members such as raw material suppliers, component manufacturers, product manufacturers, end users, logistics companies and recycling companies will need to contribute data to be captured in the DPPs. This can pose challenges related to data collection, data ownership and security unless those are addressed collectively. Authorised supply chain members need to be able to access the data and use it for their decision making related to sustainable product design, sustainable procurement, product-life extension, part-life prediction and maintenance, remanufacturing and value retention. To make this possible, interoperable systems need to be established that capture and process the data for decision making. It also poses questions for policy makers about whether they should provide incentives for DPP adoption.

In a recent publication, Zhang and Seuring (2024, p. 17) conclude that there is "an urgent need to understand the research needs in DPP-enabled sustainable and circular SCM." In this research, we address their call for action by clarifying the value of DPPs for CE and its implications for SCM research. Specifically, we aim to identify drivers and barriers to its adoption in supply chains and derive specific pathways for research that will help researchers identify the industry's pending problems.

2. Methodology

39 exploratory interviews were conducted in Scandinavia with three OEMs, their suppliers and customers, recycling partners, DPP service providers and an international standards organisation. For the OEMs, interviews were conducted with people across functions such as product engineering, compliance, quality, remanufacturing, materials and supplier collaboration. One of the OEMs is a mechatronics manufacturer (OEM1), the second is a power systems manufacturer (OEM2), and the third is a climate solutions manufacturer (OEM3). Details are provided in the supplementary file. The interviews focussed on understanding the drivers for the OEMs and their supply chain partners to consider adopting DPP, the barriers they faced and are facing in their journey to adopt DPP and the potential performance outcomes they expect. The interviews were transcribed and analysed using qualitative content analysis.

3. Drivers and barriers associated with Digital Product Passport adoption

The companies recognise that DPP is an important mechanism for achieving CE-related objectives. The interviews identify some of the key drivers: ensuring regulatory compliance, improving decision making to transition towards CE, improving transparency across the supply chain and enhancing customer engagement. Ensuring regulatory compliance and improving decision making to transition to CE are the primary drivers, which require transparency across the supply chain. Transparency also helps in enhancing customer engagement.

Ensuring regulatory compliance: The EU has taken the lead in framing regulations around CE and for the adoption of DPPs. Apart from ensuring compliance, companies must also strive to go beyond compliance to foresee future regulatory changes in the EU and other geographies and follow uniform standards across their extended supply chains. Moreover, future government tenders might require participants to consider important prerequisites of DPPs.

Improving decision making to transition towards CE: Data captured over the product's lifecycle can be analysed to assess the condition of the product at the EoU, which will facilitate decision making related to the appropriate R-strategy (Reuse, Recycle, Remanufacture, Refurbish) for the product and the individual components of the product. The companies realise that to achieve CE-related objectives, they must ensure that the suppliers receive the same grades of materials to incorporate recycled materials into their products. The need to be able to track and trace the flow of materials is particularly important for the commodities that can be easily mixed. If transparency can be provided through DPP, the different grades of materials can be sorted and separated provided data is captured at different levels of granularity of the bill of materials, reusability of the materials can be assessed and eventually increased along with extended product life and increased upcycling of materials.

Improving transparency across the supply chain. The experts we spoke to shared that their respective organisations face multiple issues, such as product data which was available only in physical documents and not digitised, little visibility of practices upstream, including missing information on whether humanitarian standards have been followed in the supply chain or not. Many organisations have started their own digitalisation efforts to improve supply chain transparency and a move towards DPP adoption is expected to provide further impetus to such efforts and potentially bring transparency across the supply chain.

Enhancing customer engagement: Companies sense an opportunity to engage with customers by adopting DPPs to display some of the relevant supply chain information to customers, thereby demonstrating their commitment beyond compliance. Accessing DPP will allow customers to make well-informed and environmentally friendly purchasing decisions, resulting in potentially increased sales. DPP data also provides an opportunity to provide additional services to end customers.

However, there also exist substantial barriers, such as developing and communicating the business case for DPP adoption, increased need for data, data standards and ensuring interoperability between systems, the extent of implementation effort needed and ensuring data security and integrity that can hinder a widespread adoption of DPPs.

Development and communication of the business case for DPP adoption: several interviewees expressed concerns and difficulty in developing the business case for DPP adoption due to difficulty in estimating the effort and investment needed and in communicating the expected gains internally as well as with supply chain partners: *"It will be a challenging task to educate the organisation to understand the value that DPPs can deliver, not only in terms of circularity impact, but also financial benefits"* (PM, OEM1).

Increased need for data, data standards, and system interoperability: One organization cannot alone collect data, ensure data standards, and ensure interoperability between systems. Therefore, an essential prerequisite for DPPs is a technical infrastructure that allows for the seamless integration of a company's systems and establishes uniform standards. In this regard, a major challenge lies in the fact that numerous legacy systems follow different data collection and processing standards and protocols.

Extent of implementation effort needed: Companies perceive the effort to be substantial that is needed to decide on the data that needs to be collected, collect those by working with supply chain partners and for setting up to collect such data. Much of the data may not be collected at all or, even if this is the case, may not be available in shareable form. The interviewees also noted the reluctance of some supply chain partners to share specific data.

Ensuring data security and integrity: A major characteristic of DPPs is data sharing across organisations. Several interviewees expressed concerns regarding the security of the data and a potential loss of control. A related major challenge is maintaining the integrity of DPPs across product lifecycles.

The interview data were analysed and coded using qualitative content analysis.

4. Future research pathways

Identifying the drivers and barriers for DPP adoption helped us define four research pathways: Policy supporting DPP adoption and regulatory compliance, use of DPP to support transition to CE, data collection, analysis, and capabilities for DPP adoption and performance outcomes and implementation support. Table 1 shows the RQs for each pathway.

Pathway 1: Policy supporting DPP adoption and regulatory compliance

Policy-related complications exist in global supply chains as specific countries and regions will lag in developing regulations or will never adopt them. Though this is also true for environmental and social due diligence legislation in supply chains, if the EU-based companies insist that their supply chain partners comply with EU regulations on DPP, certain suppliers may not be willing to comply. Moreover, if the costs of collecting data and supporting the implementation of DPP become prohibitively high, suppliers will have fewer incentives to comply. Governments may need to incentivise the OEMs while the OEMs need to incentivise their supply chain partners for DPP adoption.

The research questions for this pathway can be potentially answered using principles of mechanism design, taking a systems view and modelling using system dynamics (Forrester, 1994) and with institutional theory as the theoretical basis.

Pathway 2: Use of DPP to support the transition to CE and enhance customer engagement

Analysis of DPP data on the state of the products and their parts, an indication of failure modes or deteriorating conditions of a product-in-use can suggest improvements in product design, reduction in material content or point towards choice of alternate materials. Product data at the EoU can facilitate decision making about reuse, recycle, remanufacture, repair or usage reduction. Here, a key question for decision makers is the necessary and sufficient data granularity for the bill of materials that need to be captured.

Identification of the locations with the highest carbon and water footprint can provide inputs for redesigning sourcing, manufacturing and service networks. Manufacturing process data can help to optimise the manufacturing process to improve end-product quality and optimise the consumption of energy and water. Moreover, the data captured from DPP about usage conditions, energy consumption and carbon and water footprint of the product can potentially lead to multiple services such as predictive maintenance and failure prediction, reduction of energy and water consumption and carbon footprint and associated related services and will influence product purchase decisions for customers who will value such transparency.

Questions 1 and 3 can be answered with intervention studies using a design science approach and social network theory as the theoretical basis. Question 2 can be addressed using game theoretic mechanism design principles, while question 4 can be answered using case studies with literature support from service design and servitisation while the pricing models can be based on literature on pricing of industrial services or servitised offerings.

Pathway 3: Data collection, analysis and capabilities for DPP adoption

Much of the data needed for DPP must be collected across the extended supply chain, including the product's condition while being used by the customers. Appropriate data which needs to be collected need to be prioritised, considering their criticality concerning how the data will be used. Transparency across the supply chain is needed to achieve specific objectives related to sustainability and CE as well as the time and effort needed to collect such data while ensuring data security and interoperability across systems. Data granularity is crucial but challenging for tracking products and materials across complex systems. While detailed tracking offers insights into material composition and supports activities like sorting, testing, and maintenance, it incurs costs and can be difficult to access. While exact tracking is challenging, even limited granularity can support efficient processes and higher value retention. Companies must balance the required granularity for supporting circular value systems against the costs of data capture, storage, and analytics. Where data is essential but cannot be collected, novel approaches may be used to estimate those using text data or images. The information processing needs required for DPP will be outside the core capabilities of the majority of companies, which has already led to the rise of specialised service providers. This brings forth research questions related to their business models and how the implementing companies and the service providers can collectively develop their capabilities over time.

For this pathway, question 1 can be answered using expert knowledge, conducting experiments and by simulating the impact of the availability of multiple data points on the performance of the supply chain; question 2 can be answered using principles of mechanism design; question 3 can be answered using machine learning and image recognition techniques by following a design science intervention approach (Holmström *et al.*, 2009), while question 4 can be answered using a multiple case study approach rooted in Information Processing Theory (Tushman and Nadler, 1978) and Socio Technical Systems (Pasmore, 1988) as DPP adoption will require addressing the uncertainties and bridging the information processing gaps while recognizing both the technical needs and the behavioural issues needed for the change.

Pathway 4: Performance outcomes and DPP implementation support

Lead supply chain companies will need to develop business cases to justify the adoption of DPP beyond compliance, while companies that are not mandated to adopt but are part of an extended supply chain to consider adopting DPP should clearly understand the value drivers of the lead companies and position their efforts accordingly. For example, the value can be generated through extended product life, increased material recovery, increased upcycling of materials, and a reduced environmental footprint. This will require the selection of the performance measures (Kouhizadeh *et al.*, 2023), assessing the data needs and performance measures, the internal capabilities available, the extent of effort needed, and the additional capabilities needed, as well as assessing DPP service providers who might help bridge the capability gap.

Research to address the questions for this pathway can be conducted as a design science study working with relevant supply chain members, by incubating solutions and refining those to achieve desired objectives. A gamified approach can be followed to design experiments to demonstrate the value of DPP while considering the behavioural differences amongst decision makers across the supply chain.

Pathway	Pathway 1: Policy supporting DPP adoption and regulatory compliance	Pathway 2: Use of DPP to support the transition to CE and enhance customer engagement	Pathway 3: Data collection, analysis and capabilities for DPP adoption	Pathway 4: Performance outcomes and DPP implementation support
Research Questions	1. How can a supply chain ensure compliance with EU DPP regulations, involving global supply chain partners where such regulations will lag and will not be in force?	1. How can DPP adoption ensure environmental and social sustainability in the upstream supply chain?	1a. How can supply chain members decide on the specific data points to be included in a DPP that provide the maximum benefits in terms of transition to a CE, improved environmental and social sustainability and reduced risks while simultaneously considering the necessary investments and recurring costs including costs of ensuring data security and integrity? 1b. What is the necessary and sufficient data granularity for the bill of materials that need to be captured in DPP to support CE related decision making?	1. Which performance measures should be used to assess the outcome of DPP implementation and how will such data be collected and measured? How can a performance assessment framework for DPP be developed?
	2. Should the OEM or the brand owner be accountable for compliance and capturing the data from its extended supply chain?	2. Which contractual mechanisms will incentivise suppliers to share data, ensure data security and integrity and improve supply chain circularity performance?	2. How can a supply chain implementing DPPs ensure that data is available for the secondary raw materials it is using from other industries, which are yet to implement DPP?	2. How can the value of adopting DPP for multiple members of the supply chain be specified considering the capability gap, the effort needed, outcomes while acknowledging the regulatory and institutional differences in the different countries?
	3. Should governments create incentive mechanisms to ensure compliance and what are the appropriate incentive mechanisms?	3. How can DPP data with the condition of the product at the end-of-life be used for faster decision making to choose the optimal circular pathway for the product? How can DPP enable the transition from lower to higher levels of waste hierarchy and ensure higher value capture?	3. In the absence of quantitative data, what kind of approaches can be used to estimate the condition of the product using text data such as the maintenance and repair history or image of the product to facilitate decisions related to CE?	3. How can a business case be created for the adoption of DPP considering the potential performance impact, the investments needed and the operational costs? Which parameters have the highest impact on creating a positive business case and what are the trade-offs between data capture, DPP design, implementation efforts and the performance outcomes?
		4. How can data captured through DPP be used to provide additional value to the customers and end-users and develop services? What will be the optimal pricing models for services using DPP data where the customer will be involved in collecting and sharing such data to the manufacturer or service provider?	4. What capabilities should DPP service providers have to bridge the information processing requirements to use the DPP data for decision making related to CE and the capabilities of the implementing companies? As the implementing companies develop capabilities over time, how will the capabilities and business models of DPP service providers evolve?	4. How can the value provided by DPP facilitate customer engagement? Which aspects of transparency enabled by DPP will influence customer purchase decisions and how will those vary across industrial and consumer products and behavioural orientation of purchase decision makers ?

Table 1: The research questions for each pathway

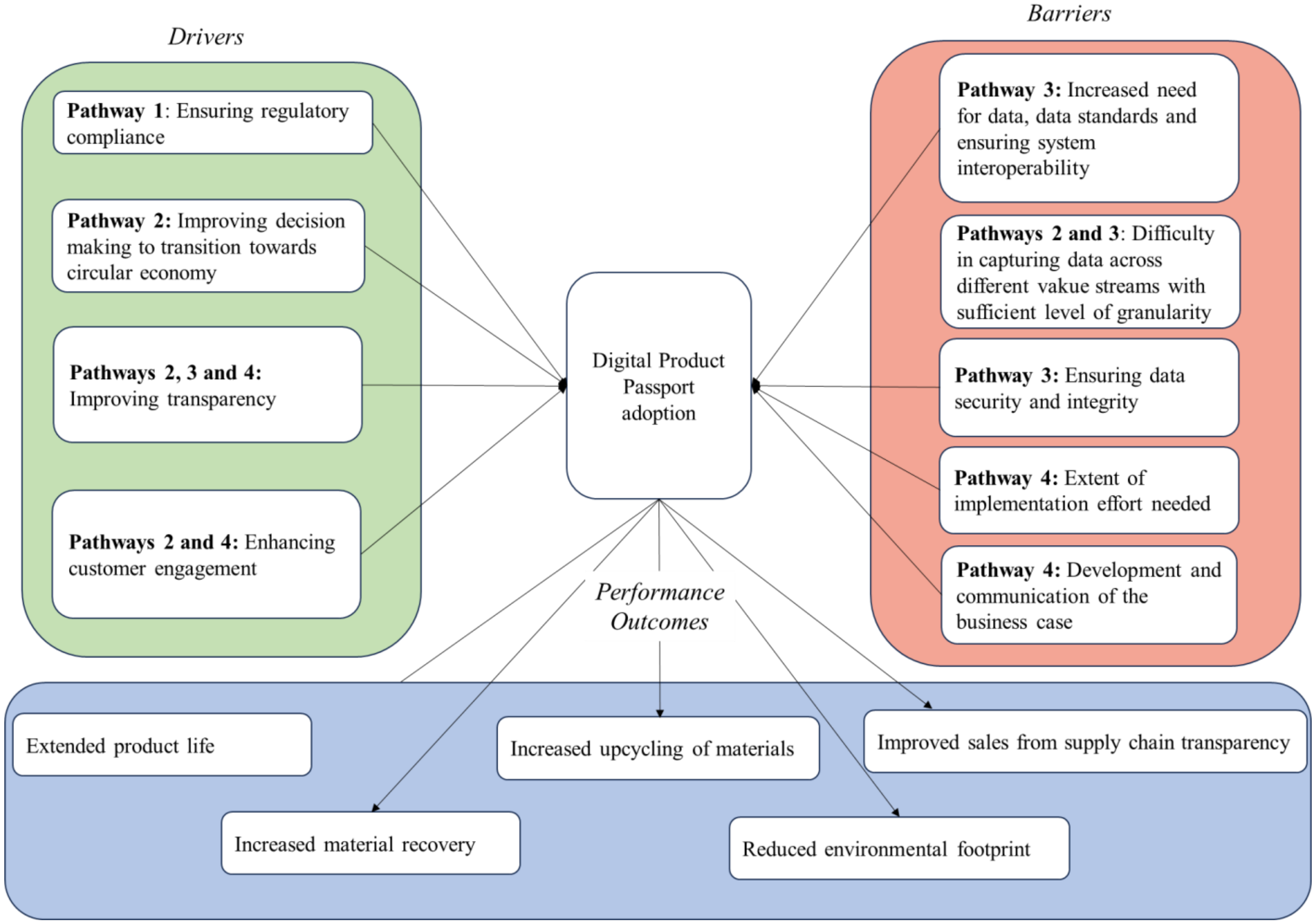

Figure 1: Drivers, Barriers and potential performance outcomes of DPP adoption

5. Conclusion

DPP offers potential, but also brings numerous challenges for both policy makers and companies related to incentivising adoption, data security, data collection and implementation efforts, developing the capabilities needed for implementation, specifying the performance outcomes and developing business cases. Hence, implementation needs to be carefully planned. DPP adoption has hitherto been underexplored in extant literature. Langley et al. (2023) provide detailed guiding principles for DPP and directions for management research but specific research questions relevant for operations and supply chain management were lacking. To close this gap we determine the major drivers and barriers of DPP adoption and identify four research pathways with relevant research questions and methodologies. The comprehensive research agenda can serve as the foundation for future studies and support the adoption of DPP. This research was conducted within the electronics supply chain. However, the research pathways and the research questions identified are equally useful for other industries, such as electric vehicles, batteries, textiles and chemicals.

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