Extended Abstract
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Accelerating Circularity in High-Tech Manufacturing: Towards a Roadmap for Implementing Digital Product Passports (DPPs) at SMEs

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Introduction

Transitioning to a Circular Economy (CE) requires innovative lifecycle management (Bastein et al., 2021). In high-tech manufacturing, SMEs face unique challenges in achieving circularity and resource efficiency. A durable digital infrastructure is needed. Digital Product Passports (DPPs) enhance transparency, traceability, and sustainability throughout multiple product lifecycles (Transitie team Advies Circulaire Economie, 2022) using detailed documentation of materials, production processes, and multiple product lifespans, enabling informed decision-making for reuse, recycling and remanufacturing (Langley et al., 2023). While larger organisations have begun adopting DPPs, SMEs struggle with financial, regulatory, and technical barriers (European Commission, 2020; TNO, 2022), including differing requirements for data access (Jensen et al., 2023). Research on DPPs remains in its early stages (Lopes & Barata, 2024).

This study explores DPP implementation challenges and opportunities in SMEs, particularly those producing and assembling electronic equipment for industry. The study is conducted in collaboration with TechValley— a consortium of high-tech SME suppliers and Original Equipment Manufacturers (OEMs) in the Netherlands —It aims to provide a roadmap for effective adoption of DPPs, addressing key barriers and leveraging digital technologies for sustainable value creation (Kollenburg, 2023).

Through a structured analysis, this research aims to address the following central question:

How can digital technologies be used to achieve practical, feasible and circular value creation through DPP implementation at SMEs in the high-tech manufacturing industry?

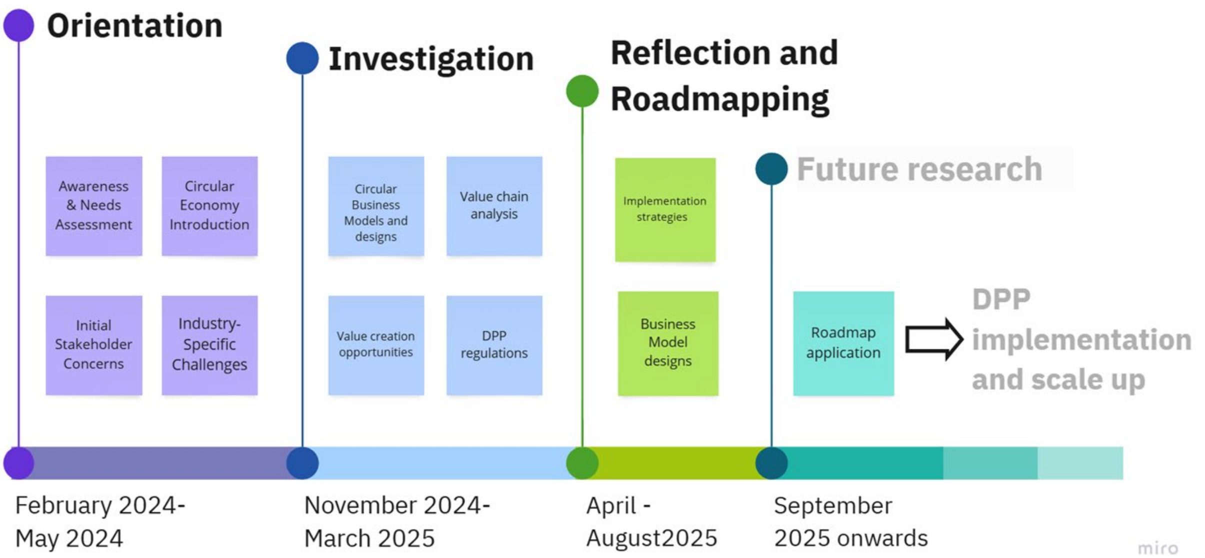

Figure 1. Methodology of the project

Methods

The research employs a multi-phased approach (figure 1), including literature reviews, stakeholder interviews, and four collaborative workshops with engineers, service engineers, business developers and managers from six companies (table 1) and two branch organisations.

Table 1. Companies from North Holland participating in the project

Role of the company	Product or service	No. of employees
Solution provider	Machine vision, robotics, data analytics and motion control	200 in 5 locations in the Netherlands
Manufacturer	High-quality coffee machines	450+ in 10 subsidiaries and two factories in Europe
Manufacturer	Blending, bagging, and transport equipment	50, one location in the Netherlands
Manufacturer	Equipment for seed processing.	75, one location in the Netherlands
Solution provider	Production automation	190, three locations in the Netherlands
Manufacturer	Specialists in 3D profiling technology within the heavy steel industry	120 in the Netherlands, 45 in Asia and 50 in the USA.

In the *Orientation Phase* (fig. 1), we gathered initial insights from stakeholders in workshops. These sessions helped create awareness of CE and DPP developments. Additionally, they helped identify key challenges, strategic priorities, and knowledge gaps regarding DPPs, laying the foundation for the subsequent workshops.

Participants were introduced to circular design and business strategies in the next two workshops (*Investigation Phase*, fig. 1) (Bakker et al. 2014). Together, we analysed the value chain, identified opportunities for value creation, and analysed how circular business models and designs can be used in circular production and product lifecycles to achieve competitive advantage. The workshops covered DPP-related regulations, such as Extended Producer Responsibility, Corporate Sustainability Reporting, and Eco-design (European Commission, 2023, 2024; Rijkswaterstaat, 2024).

During subsequent workshops in the *Reflection and Roadmapping* Phase (fig. 1), participants reflected on DPP barriers and opportunities of DPPs and the created business model designs from earlier workshops. Based on the reflections, we created a roadmap for conception, piloting, adoption and upscaling of DPPs.

The resulting roadmap aims to provide the basis for future research involving DPP implementation and scale-up.

Results

Circular design and Business Opportunities.

Participants identified key opportunities for DPPs to enhance circularity and business models at SMEs:

- **Cost Reduction**: Optimised material use, predictive maintenance, improved spare parts management, and standardised modular designs help manufacturers reduce production and service costs.
- **Improved Customer Relations**: Detailed lifecycle data supports after-sales services and take-back schemes.
- **New Business Models**: Leasing, refurbishment, resale, and "Product as a Service" models become viable.
- **Predictive Maintenance**: Traceability prevents failures, optimising downtime and workforce planning.
- **Sustainability Improvements**: Standardised records facilitate recyclability and secondary material use.
- **Transparency**: Consumers access sustainability metrics, regulatory compliance, and recycling potential.

Digital technologies Enabling DPP implementation and Product Longevity.

DPP implementation in high-tech manufacturing SMEs relies on digital technologies that enhance data traceability, resource optimisation, and predictive maintenance. Key enabling technologies include:

- **IoT & AI:** Enable automated DPP generation, real-time tracking for predictive maintenance and repair, and lifecycle analytics for reuse, remanufacturing and refurbishing.
- **Distributed Ledger Technologies (DLT):** Secures product data, ensuring transparency and regulatory compliance.
- **Digital Twins:** Simulate wear for optimising designs to improve maintenance, repair, reuse, remanufacturing and refurbishing.
- **Big Data & Additive Manufacturing:** Improve production of material recovery and on-demand spare parts.

These technologies contribute to longer product lifetimes through:

- **Predictive Maintenance:** Providing access to manuals, and performance data for reducing machine down-time.
- ***Enhanced repairability:*** Enabling efficient disassembly and supporting material recovery and circular sourcing.
- **Transparency & User Awareness**: Empowering users with lifecycle data to encourage responsible use and sustainable purchasing decisions.

While SMEs face cost and integration challenges, scalable solutions such as cloud-based AI, collaborative blockchain networks, and modular digital twins can mitigate barriers. Successful adoption requires sector-specific customisation and regulatory alignment.

Barriers to DPP implementation.
Despite benefits, SMEs face significant obstacles:

- **High Costs:** Digital infrastructure investments remain prohibitive.
- **Regulatory Uncertainty**: Evolving requirements create hesitancy in investment.
- **Data Integration Complexities**: Gaps in supply chain data and ERP system alignment hinder implementation.
- **Business Value Uncertainty:** SMEs struggle to quantify DPPs' operational and financial benefits.
- **Governance & Accountability**: Challenges in managing QR codes, traceability, and data accuracy persist.
- **Data Security Concerns**: Protecting intellectual property is a major challenge.
- **Recycling Limitations**: Some industries face material-specific recycling constraints.

Preliminary Roadmap for DPP implementation at SMEs.
A structured, SME-focused roadmap emerged from the workshops, comprising five stages:

1. **Technology Assessment:** Identify feasible digital tools, e.g. IoT, AI, and digital twinning.
2. **Business Opportunities**: Conduct SWOT analyses and stakeholder mapping for viability exploration.
3. **Piloting**: Develop a Proof-of-Concept, prototyping and testing case-specific solutions, including automated DPP generation and user tests at case studies with TechValley partners.
4. **Implementation**: Co-create implementation strategies with SMEs, researchers, and other stakeholders in the supply chain. The strategies include implementing standardised Distributed Ledger Technologies, secure data infrastructures, and collaboration agreements.
5. **Scaling Up**: Developing an innovation agenda and network for broader adoption amongst partners within and across the supply chain.

Conclusions and recommendations

Despite the clear potential of DPPs to enhance circularity, SMEs in high-tech manufacturing face significant adoption challenges, including high costs, complex regulations, and limited expertise in digital technologies. Addressing these barriers requires tailored strategies that align with SMEs' operational realities. This research identifies business opportunities through a structured methodology combining a literature review, stakeholder interviews, and participatory co-creation workshops. The proposed roadmap is designed to provide insights into business opportunities, guiding them in integrating DPPs into existing production and business models. Key findings highlight that DPPs:

- Focus on business opportunities:
  - Improve maintenance, repairability, and traceability, extending product lifecycles.
  - Enable efficient recycling and reuse by enhancing material visibility.
- Increase transparency towards suppliers and users, improving communication across the supply chain, resulting in improved value propositions and sustainable business models.
- Facilitate learning-by-doing by actively co-creating a Proof-of-Concept and prototype. Moreover, stimulate participatory testing and validation.

This study contributes to the broader discourse on the digital longevity of DPPs and hardware in high-tech manufacturing by designing and iteratively adapting durable digital infrastructures to SMEs' CE needs. Cross-industry collaboration and knowledge exchange will be essential for long-term scalability.

Future research will focus on executing the roadmap at SMEs by developing proofs-of-concept and prototypes. Additionally, we will evaluate the adoption of the designs in real-world cases by assessing contributions to circular value creation, economic viability and technical feasibility.

By bridging policy, technology, and business viability, this research supports the development of circular high-tech value chains.

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