Exploring the Role of DPPs in Smart Circular Economy: A Conceptual Synthesis

Citation for the original published paper (version of record):

de Morais, L., Silveira, C., Mintchev, M. et al (2026). Exploring the Role of DPPs in Smart Circular Economy: A Conceptual Synthesis. Lecture Notes in Mechanical Engineering: 296-304.
http://dx.doi.org/10.1007/978-3-032-21154-5_33

Exploring the Role of DPPs in Smart Circular Economy: A Conceptual Synthesis

Luana Coelho de Morais[1], Carlos Eduardo Silveira[1], Maxim Mintchev[2], Ana Carolina Bertassini[4], Meire Ramalho de Oliveira[5], Valentin Eingartner[2], Holger Kohl[2], and Mateus Cecílio Gerolamo[1,3](✉)

[1] São Carlos School of Engineering at the University of São Paulo, São Carlos, Brazil
mateus.gerolamo@usp.br
[2] Institute for Machine Tools and Factory Management, Technische Universität Berlin, Berlin, Germany
[3] Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba, Brazil
[4] Chalmers University of Technology, Gothenburg, Sweden
[5] Federal Institute of Sao Paulo, Capivari, Brazil

Abstract. This article presents a systematic literature review (SLR) that examines the strategic role of Digital Product Passports (DPPs) in facilitating transitions to Smart Circular Economies (SCE). DPPs are conceptualized as dynamic, interoperable digital records linked to unique product identifiers, facilitating multidimensional traceability across product lifecycles. The review synthesizes recent research on the conceptual foundations, regulatory drivers, technological enablers, life cycle integration, and organizational challenges. While European policies drive progress, barriers such as digital infrastructure, governance and stakeholder engagement persist, particularly in Global South contexts. The proposed conceptual synthesis integrates technological, organizational, market, and regulatory dimensions, with a focus on change management and collaborative governance. Key research gaps include a limited focus on downstream actors and behavioral factors. Findings suggest that realizing the full transformative potential of DPPs requires the coevolution of technology, organizational culture, and inclusive policy frameworks, supported by future studies in diverse economic and institutional settings.

Keywords: Digital Product Passport · Smart Circular Economy · Traceability · Organizational Change · Socio-Technical Systems

1 Introduction

The transition to a circular economy (CE) has emerged as a strategic response to the growing environmental, social, and economic concerns associated with the linear production model [1, 2]. Advancing this transition requires changes in technology, structure, culture, and information management across product lifecycles [3]. Digital Product Passports (DPPs) gained prominence as tools to enhance traceability, support sustainable

H. Kohl et al. (Eds.): GCSM 2025, LNME, pp. 296–304, 2026.
https://doi.org/10.1007/978-3-032-21154-5_33

decisions, and enable smart circular economy (SCE) models [4]. Driven by digital innovations and policies such as the CE Action Plan and the ESPR (Eco-design for Sustainable Products Regulation), DPPs are primarily applied in the electronics, construction, and textiles sectors, particularly in Europe [5, 6].

However, many DPP frameworks remain conceptual and disconnected from organizational and behavioral realities [7–9]. Barriers such as low digital maturity, fragmented governance, and institutional resistance limit their adoption, especially in emerging economies [10, 11]. Effective implementation requires a combination of technical infrastructure, institutional capacity, stakeholder trust, and adaptive leadership [4, 11, 12].

This article asks: how can a conceptual framework integrate technical and organizational functions to position DPPs as strategic tools for the SCE? The central proposition is that their effectiveness depends on embedding DPP within a socio-technical ecosystem that encompasses infrastructure, data standards, governance, culture, and stakeholder roles.

The main objective is to propose a conceptual synthesis for DPPs that represents their strategic role in the SCE by integrating functions, barriers, impacts, and actors across product life cycle stages, structured in a tabular format. Based on a systematic literature review (SLR), this study analyses five core contributions, encompassing conceptual foundations, applications, enabling technologies, and organizational challenges. The article is structured as follows: Sect. 2 details the SLR methodology; Sect. 3 presents findings and the framework; Sect. 4 discusses applicability and limitations; Sect. 5 concludes and suggests future research directions.

2 Methodology

This is a qualitative and exploratory study aiming to understand the role of Digital Product Passports (DPPs) in enabling Smart Circular Economies (SCE). A systematic literature review (SLR) was adopted as the method, following the PRISMA protocol [13] to ensure rigor and reproducibility.

Data collection was conducted in April 2025 using the Web of Science and Scopus databases. The search terms included: "Digital Product Passport*", "circular econom*", "smart circular econom*", "design", "sustainability", and "secure design". The publication period was limited to 2021–2025. A total of 105 records were identified, with 30 duplicates removed, resulting in 75 documents screened. After assessing relevance and availability, the final sample comprised 57 articles.

Content analysis followed the procedures of Whittemore and Knafl [14], including: (i) exploratory reading; (ii) data extraction based on analytical units; and (iii) categorization and subcategorization of findings.

Beyond theoretical and methodological criteria, the analysis focused on identifying stakeholder roles throughout the product lifecycle, organizational barriers, and behavioral drivers—key elements for constructing the proposed socio-technical framework.

While the SLR encompassed 57 peer-reviewed studies published between 2021 and 2025, we explored five of these contributions in greater depth, based on their theoretical richness, sectoral diversity, and relevance to the research question. These studies offered complementary perspectives on conceptual foundations, sectoral applications, traceability technologies, and organizational challenges, providing a robust foundation for synthesis. The remaining studies are not inconsequential, but their insights are integrated into the results and discussed to reinforce thematic coherence and expand contextual understanding. This two-tiered strategy balances breadth and depth: while the full SLR informs thematic trends and general patterns, the close reading of selected studies allows for deeper conceptual integration. Selection criteria were grounded in relevance to the research question, sectoral variety, and analytical clarity, rather than subjective preference.

3 Results and Discussions

3.1 An Overview on DPPs for SCE

The systematic literature review (SLR) defines DPPs as structured digital repositories linked to unique identifiers, containing product lifecycle data [15]. EU regulatory frameworks are key enablers of DPP development across sectors such as textiles, batteries, electronics, and construction [5, 16, 17]. Wan and Jiang [9] identified four core components: data sources, support, security, and access verification, noting that 64% of initiatives remain conceptual and only 20% have been implemented. Common data carriers include Quick Response (QR) codes and Radio-Frequency Identification (RFID), shaped by ESPR requirements, while blockchain is explored to ensure data integrity despite limitations in updating data during use.

Significant barriers persist, especially for SMEs, due to limited IT infrastructure, budgets, and expertise, challenges amplified in the Global South [11]. Beyond technical design, DPPs foster sustainable products by embedding lifecycle criteria such as modularity and recyclability early in design [9, 18] and guiding material selection [5, 19]. They enhance traceability, compliance, transparency, circular business models, reverse logistics, and impact assessments [15, 16, 20]. However, organizational barriers remain, especially where SMEs face low digital maturity and institutional fragility [8, 11, 12].

The literature stresses the need for inclusive, interoperable infrastructures. Future directions include using AI to estimate product longevity and integrating social sustainability indicators [21]. Addressing digital inequities [11] and broadening sustainability metrics supports a more inclusive DPP agenda, especially for underrepresented regions in the Global South.

3.2 Application of DPP in the Electro-Electronic Sector

DPPs have been applied in various sectors, including textiles, batteries, electronics, construction, and automotive [15, 18, 22]. In electronics, Koppelaar et al. [8] proposed a circular supply chain using DPPs to recover critical raw materials (CRMs) from electronic waste. A key barrier is the lack of integrated CRM traceability and coordination systems. Using literature and CircThread project data, the authors developed an architecture with product identifiers and a secure digital repository to track lifecycle data and end-of-life CRM flows.

Challenges include weak manufacturer incentives, product complexity, high costs of CRM technology, and a lack of standardized material declarations, reflecting technical and governance gaps that require validation and deeper policy analysis [5, 19, 23].

In countries like Brazil, where Waste of Electrical and Electronic Equipment (WEEE) management is evolving, existing regulations and a growing recycling sector support the adoption of DPP. Progress depends on actor coordination, overcoming data-sharing barriers, and building trust among supply chain stakeholders [11, 24].

3.3 Practical Implementation of DPPs

Çetin et al. [9] developed a Material Passport (MP) framework for European social housing, addressing existing buildings that often lack material and circularity data. Through literature review, stakeholder interviews, and a Dutch case study, they created a stakeholder map and data template.

The pilot revealed fragmented data, exposing challenges in retrofitting digital tools. To overcome this, the study proposed a digital framework that integrates Building Information Modelling (BIM), computer vision, laser scanning, web scraping, and artificial intelligence (AI) to consolidate material data and assess conditions. The model supports four CE strategies: narrow (reduce resource use), slow (extend lifespan), close (reuse/recycle), and regenerate (restore ecosystems).

AI plays a crucial role in enhancing data quality and traceability [4, 15, 25]. The integration of BIM and digital twins aligns with circularity trends and supports approaches like those by Koppelaar et al. [8]. Though only piloted, the model shows scalability. In contexts like Brazil, low digitization and informal construction highlight t the need for public investment, and organizational change.

3.4 Challenges in the Implementation of DPPs

DPP adoption faces significant challenges [5, 16, 20, 22]. Domskienė and Gaidule [12] studied the Baltic textile sector, assessing DPP familiarity, practices, and technologies. QR codes emerged as the most feasible entry point due to low cost and simplicity, while RFID, Near Field Communication (NFC), and blockchain offer greater robustness and scalability but still have limitations.

Barriers include a lack of standardization and integration, fragmented policies, poor coordination, high implementation costs, and privacy concerns. The authors recommend adjusting DPP complexity by product value, at the batch level for low-value items and at the item level for premium products. These challenges mirror those in construction [6], highlighting the need for systemic coordination In emerging economies, DPP adoption relies heavily on trust, cultural change, and governance balancing privacy, transparency, and inclusion [10].

3.5 Traceability Technologies and Structural Barriers to DPPs

Jakubowicz and Yarahmadi [12] reviewed traceability technologies for ABS plastic, a standard but hard-to-recycle material. Due to limited research, they examined both digital and physical tracking approaches. DPPs have emerged as promising tools for creating digital twins that link material composition to lifecycle data through QR codes, barcodes, and blockchain. Physical marking methods, such as photoluminescence, laser etching, and digital labels, were also considered.

The study identified four main barriers: technological (interoperability, data standardization, data quality); governance (ownership, transparency); regulatory (gaps), economic (high costs, limited SME resources); and cultural/organizational (low awareness, limited coordination, and weak cross-sector collaboration).

Although not empirically tested, the authors proposed hybrid systems that combine physical and digital tools, tailored to product type, value, and regulatory context, to address the transparency and implementation challenges discussed by Koppelaar et al. [8] and Jansen et al. [5].

The study concludes that institutional readiness is crucial for the success of DPP. In developing regions like Brazil, systemic interventions are necessary to overcome structural limitations.

3.6 Conceptual Framework: DPP for SCE

Based on the synthesis of the SLR, Table 1 summarizes the conceptual dimensions that define DPPs as enablers of smart circular economy (SCE) ecosystems.

The structure was built by triangulating empirical evidence, theoretical foundations, and gaps identified in the reviewed studies.

The Digital Product Passport (DPP) framework highlights its role as a dynamic, interoperable digital record essential for the smart circular economy. The table summarizes its strategic functions, lifecycle scope, involved stakeholders, benefits, and implementation challenges.

The DPP operates across the entire product lifecycle, engaging multiple stakeholders and technologies. Organizational culture and change management are critical, especially for SMEs and in the Global South. Despite clear benefits, overcoming technical, regulatory, and organizational challenges is key to effective adoption.

4 Conclusions

This study examined the strategic role of Digital Product Passports (DPPs) in advancing smart circular economies (SCE) through a systematic literature review, exploring how DPPs have been conceptualized, applied, and challenged across sectors, institutions and governments, to develop a guiding theoretical framework.

Findings indicate growing adoption despite persistent barriers in standardization, interoperability, governance, and stakeholder engagement. The conceptual synthesis (Table 1) emphasizes that DPPs 'effectiveness depends on integration with organizational behavior, collaboration, and inclusive policies, beyond technical design.

The central proposition - that DPPs act are socio-technical tools supporting circular practices, was confirmed. However, gaps remain in change management, the inclusion of downstream actors (consumers, repairers), and attention to organizational culture.

Table 1. Conceptual Framework of the Digital Product Passport (DPP) Ecosystem

Aspect	Details
Core	Dynamic, interoperable, and accessible digital record linked to physical products via unique identifiers
Strategic Functions	Transparency and traceability (origin, composition, manufacturing)
	Support for circular practices (repair, reuse, remanufacturing, recycling)
	Regulatory compliance and automated reporting
	Lifecycle-informed decision-making (e.g., ecodesign)
	Standardized data for interoperability and collaboration
	Consumer engagement and trust by reducing information asymmetry
Traceability Dimensions	Material traceability
	Process traceability
	Environmental traceability
Lifecycle Scope	Design, raw material extraction, use, maintenance, end-of-life
Priority Sectors	Batteries, electronics, textiles, packaging, construction [15, 16, 26–28]
Stakeholder Roles	Producers (data input), consumers (information access), regulators (verification/compliance), recyclers
Contextual Layers	Shared digital infrastructure (blockchain, IoT, cloud), interoperability, data standards
Foundational Layer	Organizational culture and change management, especially critical for SMEs and Global South contexts
Expected Benefits	Environmental (waste reduction, resource conservation)
	Economic (resilience, circular business models)
	Social (trust, safety, improved labor conditions)
Feedback Loops	Continuous improvement, regulatory learning, strategic refinement
Implementation Challenges	Technical (data standardization, platform scalability), regulatory (norm harmonization), organizational (governance, costs, training), market-related (sustainable business models)

Limitations include the qualitative nature, reliance on secondary sources, and focus on literature from 2021–2025, which may exclude emerging trends. Future research should explore empirical applications in Global South contexts, especially SMEs; assess governance and trust mechanisms; investigate organizational adoption; and develop indicators for circular and social impact measurement.

DPPs are not merely digital tools, but institutional enablers that require coevolution of technology, culture, and policy. Achieving their full potential requires interdisciplinary, locally adapted strategies, particularly in unequal contexts such as the Global South.

Acknowledgements. This study is financed by the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) - Finance Code 001, the German Research Foundation (Deutsche Forschungsgemeinschaft - DFG) and the Brazilian National Council for Scientific and Technological Development (CNPq).

References

1. Geissdoerfer, M., et al.: The circular economy – a new sustainability paradigm? J. Clean. Prod. **143**, 757–768 (2017)
2. Valencia, M., et al.: The social contribution of the circular economy. J. Clean. Prod. **408**, 137082 (2023)
3. Voulgaridis, K., et al.: Digital product passports as enablers of digital circular economy: a framework based on technological perspective. Telecommun. Syst. **85**(4), 699–715 (2024)
4. Langley, D.J., et al.: Orchestrating a smart circular economy: guiding principles for digital product passports. J. Bus. Res. **169**, 114259 (2023)
5. Jansen, M., et al.: Stop guessing in the dark: Identified requirements for digital product passport systems. Systems **11**(3), 123 (2023)
6. Adisorn, T., Tholen, L., Götz, T.: Towards a digital product passport fit for contributing to a circular economy. Energies **14**(8), 2289 (2021)
7. Wan, P.K., Jiang, S.: Enabling a dynamic information flow in digital product passports during product use phase: a literature review and proposed framework. Sustain. Prod. Consum. (2025)
8. Koppelaar, R.H., et al.: A digital product passport for critical raw materials reuse and recycling. Sustainability **15**(2), 1405 (2023)
9. Çetin, S., et al.: Data requirements and availability for material passports: a digitally enabled framework for improving the circularity of existing buildings. Sustain. Prod. Consum. **40**, 422–437 (2023)
10. Jakubowicz, I., Yarahmadi, N.: Review and assessment of existing and future techniques for traceability with particular focus on applicability to ABS plastics. Polymers **16**(10), 1343 (2024)
11. Costa, A., Crupi, A., De Marco, C.E., Di Minin, A.: SMEs and open innovation: challenges and costs of engagement. Technol. Forecast. Soc. Chang. **194**, 122731 (2023)
12. Domskienė, J., Gaidule, E.: An overview of technological challenges in implementing the digital product passport in the textile and clothing industry. AUTEX Res. J. **24**(1), 20240002 (2024)
13. Page, M.J., et al.: The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ **372** (2021)
14. Whittemore, R., Knafl, K.: The integrative review: Updated methodology. J. Adv. Nurs. **52**(5), 546–553 (2005)
15. Zhang, A., Seuring, S.: Digital product passport for sustainable and circular supply chain management: a structured review of use cases. Int. J. Log. Res. Appl. **27**(12), 2513–2540 (2024)
16. Barwasser, A., Schuseil, F., Werner, A., Jung, M., Zimmermann, N.: The digital product passport: scenario-based recommendations for the manufacturing industry. IFAC-PapersOnLine **58**(19), 1186–1191 (2024)

17. Franke, M., et al.: Towards a service marketplace to empower circular economy transition: an example application in the supply chain of textile industry. In: IFIP International Conference on Advances in Production Management Systems. Springer, Cham (2024)
18. Pohlmann, A., Popowicz, M., Schöggl, J.P., Baumgartner, R.J.: Digital product pass-ports for electric vehicle batteries: stakeholder requirements for sustainability and circularity. Clean. Prod. Lett. **8**, 100090 (2025)
19. Kebede, R., Moscati, A., Tan, H., Johansson, P.: A modular ontology modeling approach to developing digital product passports to promote circular economy in the built environment. Sustain. Prod. Consum. **48**, 248–268 (2024)
20. Adhikari, S.: The AAS and its Submodels: driving the DPP for a sustainable circular economy. ATP MAGAZINE (2025)
21. Cattaneo, M., Elia, S., Zaninotto, E.: From traceability to responsibility: integrating social impact indicators in digital product passports. J. Clean. Prod. **408**, 137186 (2023)
22. Kim, J., Moon, J., Do, Y., Kim, H., Jeong, J.: Research on a SaaS (software as a service)-based digital product passport system model for the EV battery industry value chain. WSEAS Trans. Bus. Econ. **20**, 2466–2475 (2023)
23. King, M.R.N., Timms, P.D., Mountney, S.: A proposed universal definition of a digital product passport ecosystem (DPPE). J. Clean. Prod. **384**, 135538 (2023)
24. Jensen, S.F., et al.: An ecosystem orchestration framework for the design of digital product passports in a circular economy. Bus. Strateg. Environ. **33**(7), 7100–7117 (2024)
25. Morganti, L., et al.: Data-driven and LCA-based framework for environmental and circular assessment of modular curtain walls. J. Facade Design Eng. **12**(1), 9–42 (2024)
26. Nowacki, S., Sisik, G.M., Angelopoulos, C.M.: Digital product passports: use cases framework and technical architecture using DLT and smart contracts. In: 2023 19th International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT), pp. 373–380. IEEE (2023)
27. Ferrante, M., Vitti, M., Sassanelli, C.: The evolution of circular economy performance assessment: a systematic literature review. Renew. Sustain. Energy Rev. **217**, 115757 (2025)
28. Lopes, C., Barata, J.: Digital product passport: a review and research agenda. Procedia Comput. Sci. **246**, 981–990 (2024)
29. Berger, K., Schöggl, J.-P., Baumgartner, R.J.: Digital battery passports to enable circular and sustainable value chains: conceptualization and use cases. J. Clean. Prod. **353**, 131492 (2022)
30. Geissdoerfer, M., Morioka, S.N., de Carvalho, M.M., Evans, S.: Business models and supply chains for the circular economy. J. Clean. Prod. **190**, 712–721 (2018)
31. Schick-Makaroff, K., MacDonald, M., Plummer, M., Burgess, J., Neander, W.: What synthesis methodology should I use? A review and analysis of approaches to research synthesis. AIMS Public Health **3**(1), 172 (2016)
32. Hulea, M., Miron, R., Muresan, V.: Digital product passport implementation based on multi-blockchain approach with decentralized identifier provider. Appl. Sci. **14**(11), 4874 (2024)
33. Boukhatmi, Ä., Nyffenegger, R., Größer, S.N.: Designing a digital platform to foster data-enhanced circular practices in the European solar industry. J. Clean. Prod. **418**, 137992 (2023)
34. Mendes, J.A.J., Carvalho, N.G.P., Mourarias, M.N., Careta, C.B., Zuin, V.G., Gerolamo, M.C.: Dimensions of digital transformation in the context of modern agriculture. Sustain. Prod. Consum. **34**, 613–637 (2022)
35. Campos, C.J.G.: Método de análise de conteúdo: ferramenta para a análise de dados qualitativos no campo da saúde. Rev. Bras. Enferm. **57**, 611–614 (2004)
36. Gallego-Schmid, A., et al.: Links between circular economy and climate change mitigation in the built environment. J. Clean. Prod. **260**, 121115 (2020)
37. Kirchherr, J., Reike, D., Hekkert, M.: Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. **127**, 221–232 (2017)