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Synergies Between Extended Producer Responsibility and Digital Product Passport in the Path to Sustainable Production

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Abstract

Achieving environmental goals requires transitioning towards sustainable production systems, with a key challenge being the data-intensive monitoring of entire product life cycles. This study investigates the potential of Digital Product Passport (DPP) to transform Extended Producer Responsibility (EPR) schemes by shifting focus from downstream management to proactive upstream interventions. It addresses current gaps in EPR schemes and data utilization through a methodological analysis framework, exploring possible synergies with DPP operationalization. This study highlights both opportunities and limitations of how implementing DPP could optimize resource utilization, streamline waste management, promote sustainable product lifecycles, and drive progress towards sustainable production systems.

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1. Introduction

The advent of Industry 5.0 marks a transformative shift in production systems, emphasizing a human-centric approach that synergizes advanced technologies with human intelligence and creativity [1]. In contrast to its predecessor, Industry 5.0 seeks to balance technological innovation with societal and environmental considerations [2]. This evolution underscores the necessity to address lingering environmental and societal challenges inherited from past industrial revolutions.

Despite advancements in production systems, effective data-monitoring of entire product life cycles remains a significant challenge. The complexity and data-intensive nature of tracking products from cradle to grave constrains the ability of industries to fully assess and mitigate their environmental

impacts. This limitation hinders the shift towards more sustainable and circular economic business models [3–6].

Policies and regulatory frameworks can often play a vital role in overcoming these challenges by establishing standards for environmental compliance and promoting sustainable practices. Extended Producer Responsibility (EPR) schemes have emerged as essential policy instruments aimed at redistributing the responsibility of waste management from consumers and municipalities back to producers [7]. By mandating accountability for the end-of-life consequences of their products, EPR seeks to motivate more sustainable product design and mitigate environmental impacts [8].

However, current EPR schemes often fall short in addressing the complexities of contemporary supply chains and do not adequately promote upstream interventions that could prevent waste generation and improve product longevity [9, 10].

In this scenario, the introduction of the Digital Product Passport (DPP) potentially offers a promising opportunity to enhance the effectiveness of EPR schemes. The DPP is envisioned as a digital record containing detailed information about a product's materials, components and life cycle events, thereby enabling better transparency and traceability across the value chain [11]. By integrating DPP with EPR frameworks, there is potential to shift focus from downstream waste management to proactive upstream strategies. Based on data-driven insights, this integration could possibly facilitate better resource utilization, streamline waste management processes, and promote sustainable product lifecycles.

This work aims to investigate the potential synergies between EPR and DPP within the context of transitioning towards sustainable production systems that align with Industry 5.0 principles. By identifying existing gaps in EPR schemes and examining how DPP could operationalize data utilization, this research seeks to highlight both the opportunities and challenges associated with these approaches.

2. Literature Review

The concept of EPR has emerged as a pioneering policy instrument to transition industries toward a more circular economic model. Recognizing the growing environmental challenges of linear production and consumption patterns, policymakers introduced EPR to shift responsibility for product end-of-life management from municipalities and consumers back to producers. This policy exemplifies the efforts to translate the theoretical framework of the circular economy into practical applications through regulatory measures [12].

EPR embodies the polluter pays principle, which mandates that those responsible for pollution bear the costs of managing it, while also aligning with the economic internationalization of environmental externalities. In this sense, producers should address waste pollution, an external cost, by assuming responsibility for the financial aspects of waste management. This responsibility would incentivize avoidance of waste generation, thereby also avoiding associated management expenses [13, 14].

2.1. Current Gaps in EPR Schemes

The relevance of EPR schemes as a strategic policy instrument for implementing circular economy principles in the European Union and developing countries is widely acknowledged. Numerous studies and analytical frameworks have investigated its potential advantages and inherent limitations in effectively closing the loop in product life cycles and promoting sustainability practices during the early stages of resource use and manufacturing [9, 15–18].

However, its impact on product design and the first stages of the supply chain appears more limited. EPR has had a restricted effect on driving significant changes in product design and innovation, particularly in areas such as durability, repairability [19, 20]. While it emphasizes the economic responsibilities of producers, focusing largely on financial accountability for waste management, it has not effectively

incentivized upstream design changes that could prevent waste and extend product life [8]. The collective approach to responsibility under EPR often dilutes individual accountability, leading to weaker incentives for eco-design [21]. Additionally, EPR schemes are typically more aligned with waste management practices than with the principles of a circular economy, which prioritize product longevity and reuse [17]. Consequently, the challenges in influencing upstream improvements highlight the need for stronger mechanisms that place direct responsibility on manufacturers to foster innovation in sustainable product design [19, 22].

Numerous studies have highlighted substantial data gaps and challenges associated with the implementation of EPR schemes within the context of circular economy frameworks and value chain integration [8–10, 19, 20, 23–25]. A notable lack of data concerning the effectiveness of EPR schemes in closing production loops has been acknowledged, noting that this area remains underexplored [9]. It has been suggested that EPR systems should expand their focus on recovering and treating post-consumer products to promote a circular value chain that encompasses the entire product life cycle. Furthermore, there is limited data on the efficacy of EPR legislation for reuse and remanufacturing in the EU, with a recognition that EPR's impact on advancing circular economy objectives beyond waste management - particularly regarding eco-design - is inadequately documented [10]. Additionally, the incomplete integration of environmental data across product chains undermines EPR's primary goal of holding producers accountable for their products' environmental impacts [23]. These findings underscore the necessity for enhanced data collection to improve EPR's effectiveness in supporting circular economy principles across various industry sectors.

2.2. Interconnection between EPR and DPP

Considering these identified gaps and limitations of EPR, emerging solutions such as the DPP represent a potential initiative to overcome some of these challenges. Unlike traditional EPR schemes, which often face difficulties in data capturing to guarantee accountability and transparency across the supply chain and circularity information, the DPP represents a shift in how product information is captured and shared. By using digital technologies, DPP have the potential to capture data about a product's journey from production to end-of-life, providing stakeholders with insights into its composition, origin, and environmental impact [26]. This new transformative approach could enhance EPR's effectiveness and foster the implementation of a more transparent, efficient, and sustainable approach to product lifecycle management.

While DPP holds significant potential to transform product lifecycle management and promote sustainability, it is essential to recognize that it will not achieve all targets of circular economy on its own [11]. However, while not a standalone solution, DPP could serve as a key instrument within a well-orchestrated policy mix. In this scenario, the concept of DPP

can amplify its impact when integrated with complementary and existing policy instruments, such as EPR schemes.

The literature review disclosures a notable research gap in examining the interactions between EPR schemes and the emerging concept of DPP. While both policy instruments aim to enhance sustainability and accountability in supply chains, there has been limited exploration of their potential integration. EPR has primarily focused on shifting waste management responsibilities from consumers to producers, yet it has had a limited impact on driving substantial changes in product design, particularly concerning durability, reparability, and overall sustainability. Additionally, the emphasis on financial responsibility in EPR has not effectively incentivized upstream design changes aimed at waste prevention and product life extension. On the other hand, DPP offers detailed data flow throughout a product lifecycle and could provide a more dynamic framework for facilitating informed decision-making in product design and sustainability practices. Despite potential benefits, integrating DPP and EPR may also present challenges. This research aims to evaluate how the DPP can enhance EPR operations and improve regulatory compliance while also identifying potential obstacles to their effective integration.

3. Methodology

3.1. Validation Approach

The DPP concept is relatively new, leading to a notable gap in the literature regarding its operationalization and practical use. While the DPP emphasizes the importance of capturing diverse datasets to improve transparency and traceability throughout the product lifecycle, the specific mechanisms for utilizing this information remain unclear, as it has not yet been implemented. Discussions surrounding DPP within the regulatory framework have primarily centred on how information will be presented to stakeholders across the supply chain and the technological tools to be employed, but not on the actual use of this information [27, 28].

In this light, this research is structured with a focus on identification of potential synergies between DPP and EPR by investigating how these regulatory frameworks can be integrated to optimize resource use, streamline waste management and foster sustainable product lifecycles through data captured through DPP, addressing acknowledged gaps in EPR schemes.

3.2. Methodological Approach

A SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis has been conducted to provide a comprehensive overview of the potential outcomes arising from the integration of DPP and EPR. This analysis systematically identifies and evaluates internal strengths and weaknesses, alongside external opportunities and threats, offering insights into the effective interaction of these frameworks.

The first step in the SWOT analysis methodology consisted of identifying the strengths and weaknesses of both DPP and EPR systems based on the literature review. The purpose of this step is to define each system in terms of its positive attributes and challenges. For DPP, strengths involved attributes such as transparency, lifecycle data, and traceability, while weaknesses could include high implementation costs and challenges with data standardization. For EPR, strengths included producer accountability, improved recycling rates, and the creation of recycling markets, while weaknesses might involve gaps in data tracking and a limited influence on upstream product design. Identifying these strengths and weaknesses is necessary for analyzing the interaction of these two systems under the cross-impact analysis.

The second step included conducting a cross-impact analysis to evaluate how the strengths and weaknesses between DPP and EPR might interact in a hypothetical integration scenario, leading to identification of potential opportunities and threats, as shown in Figure 1.



Figure 1. Combination of Strengths and Weaknesses between DPP and EPR

Synergistic opportunity refers to situations where the strengths of both framework systems complement one another, resulting in a synergy that fosters new opportunities. This type of opportunity arises when the integration of both systems enhances their positive attributes, thereby unlocking potential for improvement and innovation. Compensatory opportunities occur when the strength of one system effectively mitigates or addresses a weakness of the other. This type of opportunity emphasizes the importance of balancing out limitations, where the positive attributes of one framework serve to fill the gaps or overcome the challenges faced by the other. Threats occur when the weakness of both systems converge, resulting in compounded risks or negative impacts. Rather than providing compensation, these weaknesses may reinforce one another, leading to more significant challenges. When the vulnerabilities of the two frameworks overlap, they generate risks that, if left unaddressed, could hinder the success of their integration and diminish the potential benefits that could arise from their synergy.

In the final step, an analysis and reporting of the findings derived from the cross-impact analysis were conducted. This phase aimed to systematically consolidate the most significant and compensatory opportunities, alongside the identified threats. The primary objective was to elucidate the potential benefits arising from the integration of DPP and EPR, as well

as to delineate the associated risks. The results were graphically represented through Venn Diagrams, effectively illustrating the interactions and interdependencies between the two systems.

4. Results and Discussion

4.1. Synergistic Opportunities

Figure 2 summarizes the identified synergistic opportunities, emphasizing the strengths of both systems. The intersection within the diagram illustrates the potential outcomes resulting from their interaction, which fosters a synergy that can facilitate new opportunities.

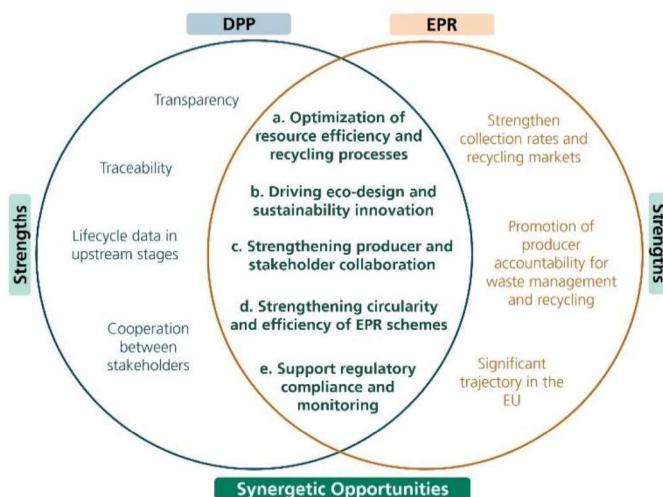


Figure 2. Synergistic opportunities between DPP and EPR

a. Optimization of resource efficiency and recycling processes:

DPP may enhance recycler's ability to separate and process materials, potentially improving recycling rates. This synergy might increase the profitability and efficiency of recycling markets, reduce landfill waste, and facilitate the reintegration of materials into production cycles.

b. Driving eco-design and sustainability innovation:

specific data on product recyclability, material impacts, and durability provided by DPP might be integrated into design processes. EPR's financial incentives, such as waste management costs, could encourage producers to adopt design-for-recycling principles, leading to products that are easier to reuse, recycle or remanufacture.

c. Strengthening producer and stakeholder collaboration:

This integration might foster improved collaboration across the value chain, enabling more effective cooperation among producers, recyclers and regulators. Enhanced communication and data flow allow stakeholders to optimize collection, recycling, and disposal processes, as well as the use of recycled materials in product design, promoting a cohesive and efficient system that ensures circularity within the EPR framework.

d. Strengthening circularity and efficiency of EPR schemes:

by providing accurate information on material composition and potential reuse or recycling options, DPP

can aid producers in meeting EPR resource recovery requirements. This collaboration is expected to retain more materials within the economy, reducing dependence on raw materials and promoting sustainable production and consumption practices. Additionally, EPR may implement new targets focused on circularity, such as the percentage of recycled materials in products and the rates of reused or repaired items, which could contribute to extending products lifespans.

- e. **Support regulatory compliance and monitoring:** the integration of DPP's traceability and transparency with EPR's accountability framework can significantly enhance regulatory compliance. Incorporating DPP data into EPR systems provides regulators and producers with better visibility across entire product lifecycle, facilitating more accurate adherence to waste management, recycling targets, and end-of-life responsibilities. This synergy may strengthen the enforcement of environmental regulations in the EU, improve reporting accuracy, reduce non-compliance, and encourage responsible waste management practices.

4.2. Compensatory Opportunities

Figure 3 presents the results of the compensatory opportunities, illustrating how the strengths of one system (DPP or EPR) can counterbalance the weakness of the other. The intersection in the diagram indicates areas where compensatory actions can effectively address limitations, potentially resulting in improved outcomes.

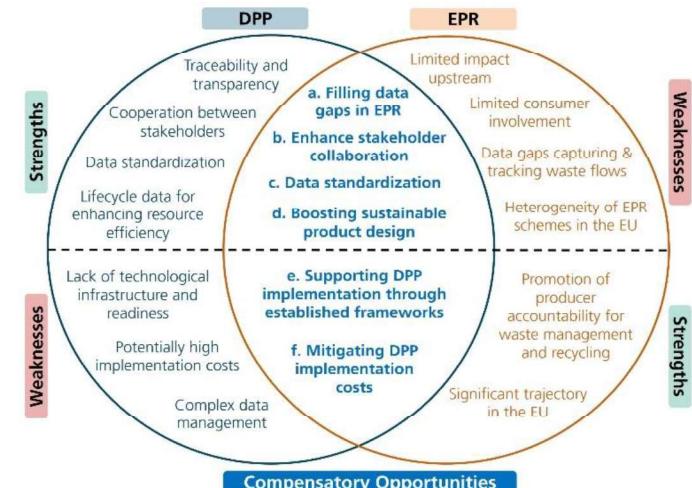


Figure 3. Compensatory Opportunities between DPP and EPR

a. Addressing data gaps in EPR through traceability and transparency mechanisms:

DPP's capability to enhance tracking and transparency may mitigate existing data deficiencies in EPR systems. The integration of lifecycle data streams could improve visibility into waste flows and material recovery processes. This integration also supports data-driven decision-making, enabling stakeholders to identify areas for improvement and optimize resource allocation.

b. Enhance consumer involvement through stakeholder collaboration: integrating DPP data into consumer-facing platforms, such as applications or product labels, could inform consumers about the environmental impacts of their products and appropriate disposal methods. This increased transparency may educate consumers on their role in waste management and encourage greater environmental awareness.

c. Promoting data standardization: DPP's provision of standardized, transparent data may facilitate the harmonization of EPR schemes across diverse countries and sectors. Utilizing DPP to establish a unified digital record of product lifecycles could simplify compliance for producers and regulators. This standardization may reduce the complexity associated with navigating multiple EPR systems, thereby enhancing compliance efficiency and improving the enforcement of environmental standards internationally.

d. Boosting upstream sustainable product design: DPP's lifecycle data stream may improve eco-design practices, while EPR's financial incentives for sustainable design could ensure producers consider these insights. Through this integration, producers might be encouraged to design products that are more recyclable, utilize fewer raw materials, and generate less waste. This compensatory opportunity pushes the upstream improvements in product design that EPR alone has struggles to achieve.

e. Supporting DPP implementation: EPR's established framework and long history in the EU can serve as a foundation for the gradual integration of DPP systems across various sectors. The extensive adoption of EPR in the EU can facilitate technological investments and infrastructure development to support DPP implementation. Since EPR systems are already operational, DPP adoption could be phased in with assistance from existing Producer Responsibility Organizations (PROs), allowing for a smoother transition.

f. Mitigating DPP implementation costs: EPR's focus on producer accountability may hasten implementation of DPP by encouraging producers to invest in its infrastructure as part of their responsibility for managing product lifecycles. Integrating DPP into existing EPR frameworks could allow multiple producers within the same sector to share costs, for example, through PROs. This cost-sharing approach could make it more feasible for companies to adopt DPP systems. Additionally, it could enhance data transparency and product traceability, thereby supporting the effectiveness of EPR schemes.

4.3. Threats

Figure 4 summarizes the potentially associated threats with integrating DPP and EPR, highlighting potential risks that might emerge from the intersection of both system weaknesses. The overlapping area in the diagram illustrated the compounded risks, which could jeopardize the overarching objectives of sustainability in the context of this integration.

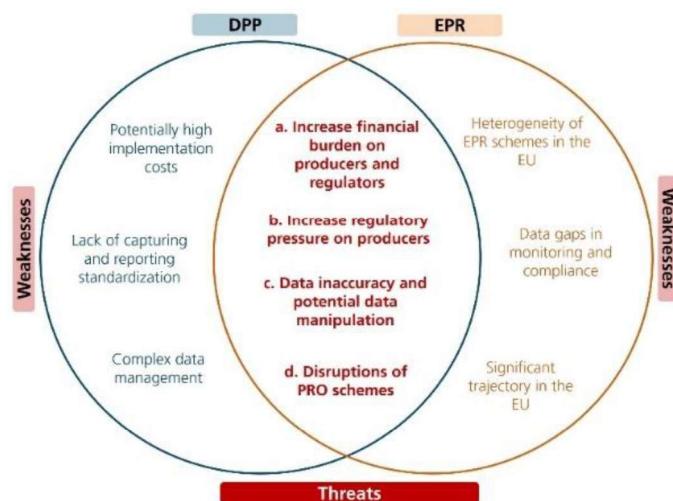


Figure 4. Potential threats between DPP and EPR

- a. Increase the financial burden on producers:** implementing DPP will require substantial investments in digital infrastructure, digital sustainability management systems, and staff training for producers. Simultaneously, producers must fulfill EPR obligations, including financing collection and recycling systems. The requirement for real-time data tracking, reporting, and auditing to comply with both DPP and EPR regulations may increase costs for producers, particularly small and medium-sized enterprises. These high implementation costs could result in a slow adoption rate, potentially leading to compliance gaps and hindering progress toward sustainability targets.
- b. Increase regulatory pressure on producers:** producers may face increased regulatory pressures from the data capture and traceability requirements of both DPP and EPR, which focus on product end-of-life and may extend upstream in the supply chain. This could create a significant compliance burden, especially for those operating across multiple jurisdictions with varying regulations. The integration of both systems may lead to regulatory overload, requiring companies to allocate substantial resources to compliance rather than other areas of optimization.
- c. Data inaccuracy and manipulation:** there is a potential risk that producers, in their efforts to comply with increasingly stringent EPR targets both upstream and downstream, may inadvertently misreport or manipulate data provided through DPP systems, which could create a misleading perception of their products' sustainability. This situation, coupled with the complexities of monitoring data accuracy, may challenge the integrity of both frameworks, complicating compliance enforcement for regulators and affecting consumer trust in environmental claims. Additionally, inconsistent data reporting across global supply chains could heighten this risk, allowing variations in regulatory enforcement to impact adherence to sustainability requirements, ultimately affecting accountability and environmental outcomes.
- d. Restructuring of EPR schemes and potential disruptions of PRO schemes:** the implementation of DPP may

necessitate a restructuring of EPR systems, particularly the functions of PROs. Currently, PROs handle collection, recycling, and reporting responsibilities on behalf of multiple producers, offering a centralized compliance approach. However, the introduction of DPP may require each producer to manage their own product lifecycle data directly, significantly changing the role of PROs, particularly in the end-of-life stages of waste management and disposal. This transition could potentially disrupt established waste management systems in affected sectors, leading to confusion and operational challenges for producers that depend on PROs for compliance support in managing the end-of-life of their products.

5. Conclusion and Outlook

This work has evaluated the synergistic integration of DPP with EPR and its potential to enhance sustainable value chains. The study emphasizes the limitations of current EPR schemes, which primarily focus on end-of-life management activities, such as collection, recycling, and disposal. While these initiatives have made strides in improving material recovery, they often fail to address critical upstream practices, including sustainable material sourcing and eco-design. By incorporating DPP's capabilities for tracking materials and providing comprehensive lifecycle data streams, stakeholders can gain insights that facilitate compliance monitoring throughout the entire product lifecycle. This integration may also encourage the adoption of practices focused on reuse and repair, ultimately contributing to a more sustainable approach to production systems.

However, this work also acknowledges several challenges associated with implementing this integrated approach. The potential for increased costs and data management complexities could impose a heightened regulatory burden on producers, complicating compliance efforts. Furthermore, to effectively leverage DPP data, it will be necessary to implement policy adjustments that include the establishment of clear data standards, the introduction of incentives for eco-design, and the setting of comprehensive sustainability targets. These actions can be vital for transitioning from theoretical concepts to practical applications and fostering truly sustainable and circular production systems towards Industry 5.0.

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