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# Integrating blockchain with digital product passports for managing reverse supply chain

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**Abstract**

The reverse supply chain (RSC), vital for circular economies, faces considerable challenges, including transparency deficits, trust issues, and inefficient information sharing. Blockchain can enhance transparency and traceability in circular economy practices, but it has limitations in providing detailed, product-specific lifecycle data. In contrast, the digital product passport (DPP) is designed to provide this detailed information, offering comprehensive, high-quality data across a product's entire lifecycle. By integrating DPP, the inherent data limitations of blockchain can be overcame, making it a more useful tool in promoting sustainable practices. The aim of this research is to explore integrating blockchain technology and the DPP to manage RSC for circular economy practices. To achieve this, a novel conceptual framework is presented that merge blockchain with DPP, potentially enhancing information efficiency throughout the entire lifecycle of end-of-life products and reducing uncertainties in RSC processes.

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*Keywords:* Reverse supply chain; Blockchain; Digital product passport; Sustainability

## 1. Introduction

The reverse supply chain encompasses a series of processes that involve recovering parts and end-of-life products from consumers and reintegrating them into the market or production line. As the core component in advancing various circular economy practices, the RSC faces challenges about transparency, trust, and efficient information sharing [1]. Inconsistencies in information flow regarding resources, products, and processes not only raise consumer concerns about product safety, reducing enthusiasm for recycling, but also hinder the progress of the circular economy [2]. Such inconsistent and inaccurate information flow undermines stakeholder trust, resulting in unstable collaborations. Moreover, the unpredictability inherent in RSC (i.e., quantity, quality, timing) makes production planning and control more complex than in forward supply chain, poses challenges for stakeholders in making informed decisions and planning processes [3, 4].

Blockchain can support to alleviate existing barriers for circular economy practices by facilitating transparency and traceability [5]. As a technological paradigm, blockchain integrates an array of computer technologies, encompassing peer-to-peer (P2P) networks, consensus algorithms, smart contracts, cryptography and other information technologies [6]. While blockchain technology shows promise in addressing RSC management challenges, research in this area is still in its infancy. Additionally, blockchain is limited in presenting detailed data content. Conversely, the DPP, perceived as a technology bridging information gaps, offers

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high-quality lifecycle data to value chain stakeholders [7]. DPP provides comprehensive product information, offsetting the drawbacks of blockchain, and its user-friendly design mitigates the blockchain's complexity. Specifically, DPP data from various stakeholders initiate new transactions within the P2P network, which are then broadcast using asymmetric encryption to ensure secure transmission. Other blockchain nodes receive and validate these transactions. Validated transactions are compiled into a new block and confirmed through a specific consensus mechanism. Although the integration of DPP and blockchain specifically for RSC information remains largely unexplored, there is an opportunity to enhance management of the RSC. The aim of this research is to investigate the integration of blockchain technology and DPP to better manage RSC information.

## 2. Literature review

### *2.1 Scope and selection*

High-quality journal papers with an impact factor greater than 3 are the reliable sources for this research. Three citation databases are chosen, including Web of Science, Scopus, and Google Scholar. The following keywords are utilized as query string: "blockchain" AND "reverse supply chain OR closed-loop supply chain", "digital product passport" AND "reverse supply chain OR closed-loop supply chain", "blockchain" AND "digital product passport". Although the term "blockchain" was introduced in 2008 and initially applied primarily in the financial sector, the first academic journal paper discussing the combination of blockchain and supply chain appeared in June 2017. Thus, the search timeframe is set from June 2017 to May 2024.

A total of 111 papers are initially selected after theme searching. This selection is refined to 100 after filtering by article type. Further screening based on content and the impact factor of the journals resulted in the final selection of 34 papers. Based on these selected papers, the application of blockchain technology in RSC and relevant research on DPP are reviewed in the following sections.

### *2.2 Application of blockchain in reverse supply chain*

The integration of blockchain into supply chain management has particularly attracted numerous scholars and practitioners [8, 9]. However, the adoption of blockchain in the RSC is comparatively rare [10-13], with specific applications in industries like energy vehicle batteries [1], waste electrical and electronic equipment [10], food processing industry [14], automotive industry [15], waste [16], and engine industry [17].

Scholars are exploring blockchain to address existing issues in RSC. For example, a triple retry framework for circular blockchain platforms in the RSC is proposed [18]. For product recall management, an Ethereum blockchain integrated with the interplanetary file system is employed to handle large data in the automotive industry [19]. Another Ethereum solution is developed to prevent return fraud of large household appliances in reverse logistics [20]. For end-of-life products management, a blockchain-based model enhances solid waste management efficiency and optimizes waste trade among entities [21]. In managing reverse logistics, a conceptual framework for blockchain in RSC networks aims to attain sustainability goals [22], while a commodity information traceability scheme based on blockchain improves sustainable development [23].

Regarding recycling management, a blockchain token incentive model addresses the issue of unqualified recyclers [24]. The benefits of blockchain in both a closed-loop supply chain and a reverse omnichannel are also explored [25]. Blockchain can raise collection rates and reduce environmental pollution [26], and address inconsistency between actual and theoretical recycling amount [27-29]. Moreover, the impact of government supervision on adopting blockchain for cooperative recycling strategies is examined [30], and government investment in blockchain platform can facilitate the recycling of waste products [31]. A blockchain-based remanufacturing-centric recycling framework orchestrates transactions within the recycling market by tracking the quality attributes of products [32], and choosing an appropriate blockchain adoption strategy can increase remanufacturing rate [33].

Additionally, the integration of blockchain technology with other Industry 4.0 technologies such as the Internet of Things (IoT) enhances the sustainability of RSC [34]. For instance, conceptual models for both open and closed-loop digital RSC are proposed for asbestos waste treatment by combining blockchain and IoT [35]. A framework for the virtual closed-loop supply chain based on novel blockchain and IoT technologies is developed [36]. To determine the optimal trade-into-upgrade policy, a blockchain-enabled disassembly-to-order system with IoT-embedded products is presented [37]. Furthermore, a blockchain-based system, combined with IoT and radio frequency identification (RFID) technology, ensures transparency in the reverse flow [38].

### *2.3 Digital product passport*

The DPP, an emerging concept for digitalizing product life cycles, presents significant opportunities to enhance circular economy practices [39, 40]. DPP compiles critical data summarizing a product's origin, composition, durability, reparability, dismantling options, and end-of-life handling instructions [41]. Nevertheless, it is imperative to address information security risks, as the potential for data duplication and alteration within IT systems highlights the need for verifying the origin, integrity, and compliance of DPP information to maintain trust and confidentiality throughout the value chain [42].

Combining blockchain technology with DPP offers a promising way to overcome DPP limitations. The literature highlights the benefits of blockchain-based product passports in asset management, ensuring quality compliance, identifying counterfeit products, and enhancing the product and service safety, thereby bolstering confidence in project managers about using high-quality materials [43]. Systematic quality control and registration processes are crucial to keep solar passports updated, a task facilitated by blockchain [44]. A sustainable plastic waste management method combining DPP with blockchain technology is introduced [45]. In the electric vehicle battery supply chain, the role of blockchain and DPP in meeting circularity needs

in battery tracking and capability sharing is analysed [46]. A resources passport, acting as a digital twin and consolidating data on a blockchain platform, facilitates communication with various identification systems [47].

Furthermore, adopting DPP can enhance the value recovery of reused and remanufactured products [44]. The BAMB [48] proposal involves collaboration among partners from seven countries, integrating DPP with business models, and policy agendas for circular economy implementation. DPPs, by emphasizing material characteristics and their value for recovery and reuse, help determine the market value of used building materials [48]. A conceptual supply management system design using DPP for critical raw materials recovery is presented, where DPP acts as a universal product identifier and facilitating information exchange through a dedicated web portal [49].

## 3. Framework structure

To comprehensively manage RSC management information, the first step is to record all data during the forward logistic flow. This is crucial, as the data from the forward supply chain system lays the foundation for managing RSC information. In the forward logistic flow of the value chain, cradle-to-gate information is generated by various entities, including designers, material suppliers, component producers, manufacturers, and distributors. Conversely, the reverse logistics flow entails the return of product for repair and maintenance, and the recovery of end-of-life products. The gate-to-cradle information in reverse logistics flow is created by entities like repair and maintenance providers, collection centres, and disassembly and inspection centres. Driven by study [15], this value chain operates in a logical sequence, forming a cross-enterprise, cross-department, end-to-end business process. Considering the value chain encompassing both forward and reverse logistics, a framework for managing RSC information that integrates DPP with blockchain is proposed (see Figure 1). This innovative framework is structured into lower-level applications (i.e., blockchain layer and data layer) and upper-level applications (i.e., user interface layer and application service layer). The lower-level applications lay the foundational technology support and handle data processing within the system, thereby facilitating user interaction and functionality at the upper levels. Meanwhile, the upper-level applications deliver intuitive user interfaces and application services, drawing on the foundational support of the lower-layer applications. These four layers are closely connected through the continuous exchange of data and services.

### *3.1 User interface layer*

Guided by study [1], the user interface layer can facilitate direct user interaction. It controls system access through a user access mechanism, providing users with a corresponding functional interface.

***Login page*** Login page features robust security authentication, allowing users to manage their personal data and access the system. It supports multi-factor authentication for enhanced security.

***Digital product passport management interface*** This interface facilitates creation, updating, querying and deletion of DPP. It features notifications, reminders, and graphical tools for editing and viewing passport information, simplifying the comprehension of material and product lifecycle for users.

***Blockchain management interface*** This interface provides access to blockchain nodes and smart contracts, enabling users to monitor blockchain transactions and events.

***Reverse logistics interface*** Dedicated to managing the reverse logistics process, this interface supports product recovery, reuse and reintroduction into the supply chain with real-time monitoring capabilities.

***Product traceability interface*** This interface allows users to track product lifecycle using unique identifiers and includes visual tools to understand the history and current status of the product.

***Collaboration tool interface*** Designed to support user collaboration, this interface offers messaging, discussion area, and document sharing features to enhances communication and cooperation among various participants.

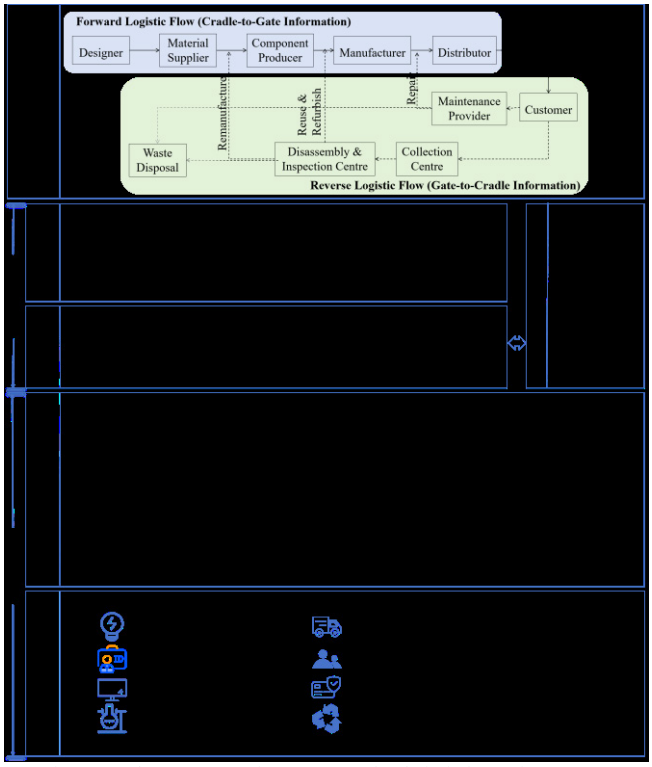



Figure 1. The structure of reverse supply chain information system

### *3.2 Application service layer*

Influenced by research [1], the application service layer not only provides applications for users within the information system, but also integrate with external systems, such as enterprise resource planning (ERP), customer relationship management (CRM), supplier relationship management (SRM), third party logistics (3PL), industry and government regulatory systems, and scientific research institutions. It standardizes external database information to ensure compatibility with the proposed information system.

***Digital product passport management module*** This module handles the creation, registration, and updating of product data, ensuring data security and accuracy with strict access and permission controls. It also offers audit, storage

backup and data logout functions.

***Product tracing and traceability module*** While the DPP management module provides basic tracking, this module caters to specialized tracking needs in sectors like medicine and automotive, ensuring product information security, compliance, and credibility with traceability records, verification, anti-counterfeiting technology, and abnormal event recording.

***Information sharing and collaboration module*** This module promotes information sharing and collaboration among various links, maintaining information consistency and reliability through logistics information publishing, collaborative management tools, important notice announcements, and access to industry policies and regulations and reverse logistics enterprise details.

***Blockchain management module*** This module provides a reliable and efficient digital infrastructure with comprehensive node management, stringent security measures, efficient smart contract execution, continuous data synchronization, and node monitoring, supporting product manufacturing, sales, reverse logistics.

***Customer response module*** This module aims to ensure timely and accurate customer needs responses, processing and analysing feedback, including satisfaction surveys and complaints. It offers personalized service, comprehensive support, order tracking, reverse logistics management, and account management, enhancing customer experience, brand loyalty, and market competitiveness.

***Reverse logistics management and analysis module*** This module focuses on efficiently managing returns, recycling processes, and inventory while optimizing cost-effectiveness. It integrates product disassembly, sorting management, recycling prediction, flexible recycling decision-making, and comprehensive network planning with advanced data analysis. This can help reduce uncertainty and improve control in reverse logistics process [50], supported by a predictive model [51].

### *3.3 Blockchain layer*

Motivated by the research [52], the blockchain layer can manage the distributed ledger of the RSC.

***Consensus mechanism*** This protocol enables decentralized verification of transaction facts by peer nodes. An effective consensus mechanism, such as proof of work (PoW), proof of stake (PoS), delegated proof of stake (DPoS), or byzantine fault tolerance (BFT), ensures blockchain security and consistency [8].

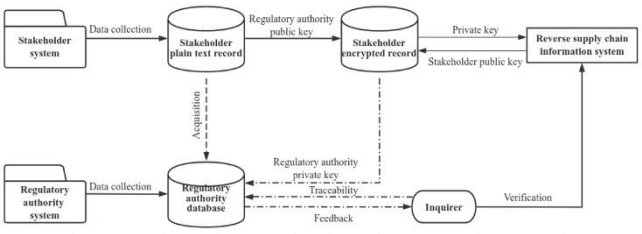



Figure 2. Information security through asymmetric encryption

***Asymmetric encryption technology*** To safeguard sensitive data, asymmetric encryption restrict access rights, precenting unauthorized access [53], as illustrated in Figure 2. Stakeholders encrypt data using the public key of the regulatory authorities, sign it with their private keys, and upload it to the blockchain [54]. For product verification, inquirers decrypt using the public key of stakeholder. For traceability, regulatory authorities use a combination of the stakeholder's public key and their private key to access the data, ensuing sensitive information remains protected.

***Smart contract*** Originally intended to digitize legal promises, smart contracts automate are automatically generated and executed, enabling trusted transactions between two parties in the absence of a third party [55]. A smart contract encompasses generation, response, and execution stages [56]. Stakeholders define contract specifics, which are implemented and tested through scripts and algorithms [57]. Once deployed, the contract executes automatically under predetermined conditions, monitoring stakeholder behavior and ensuring durability by being stored on the blockchain [58].

***Blockchain data structure*** Each block consists of block header and body [32]. Transaction data within the block body, structured as a Merkle tree, generates a root hash value for the header. Utilizing avalanche effect inherent in hash functions, any alteration in the Merkle tree data results in a corresponding change in the root hash value, thus safeguarding block data integrity. Block headers record timestamps, linking new blocks to previously created blocks.

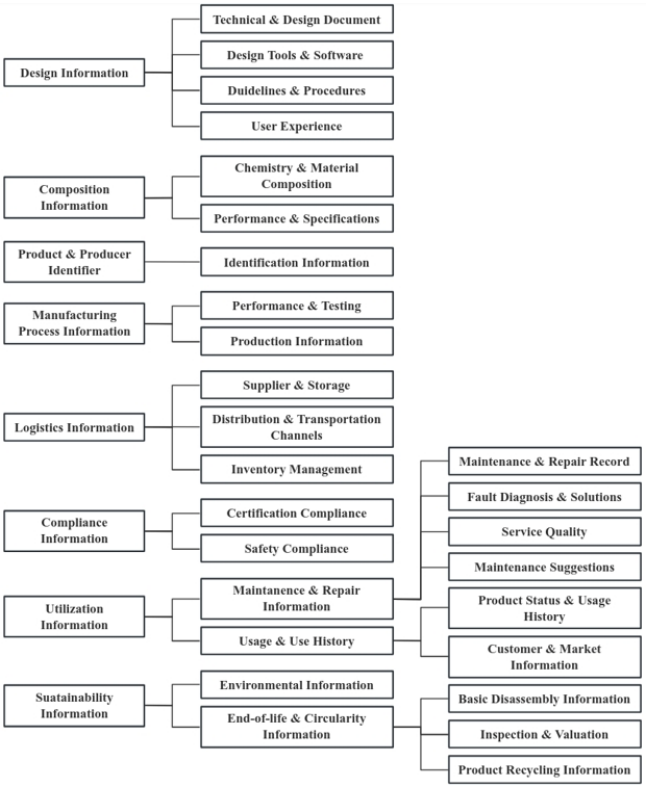



Figure 3. Main categories and their sub-categories of DPP

### *3.4 Data layer*

Inspired by the researches [18], the data layer is essential to manage multiple data types to support DPP management, blockchain interactions, and other information system functions.

***Digital product passport data*** This data enables stakeholders in the value chain understand product

composition, environmental impacts of production and use, and recycling solutions at life cycle end [59]. Guided by the manufacturing industry DPP classification [60], this research classifies DPP into main categories such as design, composition, identifier, manufacturing process, logistics, compliance, utilization, and sustainability information, with sub-categories depicted in Figure 3.

***User data*** This data includes identity information like usernames, passwords, roles, rights. Operation logs record user activities for auditing and security monitoring.

***System configuration and setting*** The data encompasses configuration parameters, setting options, notifications, and reminder. It stores system metadata like smart contract addresses and blockchain network configuration.

***Security data*** Security data contains such as encryption keys, digital signatures, access control rules, and records of security events and threats.

***Historical data and backup*** This data store historical data for tracing product life cycle and system operation history. Regular data backups ensure recovery in case of system failure or data loss.

## 4. Discussion

A framework is designed to manage RSC information by integrating blockchain technology with DPP. More specifically, the RSC faces issues like uncertainty, lack of transparency, and low trust. Blockchain, known for its shareability, immutability, and security, shows potential in addressing these issues. This research proposes a blockchain-based framework that aims to simplify the complexity of the supply chain by resolving these issues. In addition, DPP can effectively encompass information spanning from cradle-to-gate (forward logistics) to gate-to-cradle (reverse logistics), enhancing data precision and timeliness. This research identifies key stakeholders across the entire supply chain, classifies DPP into eight main categories based on the value chain, and elaborates on their respective sub-categories.

This integration addresses blockchain's limitations in data detail presentation, with DPP filling the gaps. Furthermore, blockchain not only clarifies the implementation path for DPP but also ensures information security and efficient sharing, offsetting DPP's limitations. Adapting blockchain and DPP in RSC management has the potential to enhance value chain trust, transparency, traceability, safety, operability, as well as improve product and material value recovery, all while minimizing potential information security risks during data transformation. This research provided a novel attempt, which indicates that the adoption of integrating blockchain technology and DPP is still in the early stages. The proposed framework can potentially improve information efficiency across the entire lifecycle of end-of-life products and reduce uncertainties in RSC processes. The proposed framework shows potential for broader application in various industries, such as electrical and electronic equipment, luxury watches, and smartphones.

## 5. Conclusion and future work

A conceptual framework is presented by merging blockchain with DPP, potentially enhancing information efficiency throughout the entire lifecycle of end-of-life products and reducing uncertainties in RSC processes. Despite the proposed framework indicates opportunities for future studies, this research has some limitations. This research is predominantly qualitative, and the proposed framework needs to be validated through qualitative and quantitative studies involving simulation. Although this research is promising and suggest it is worthwhile to invest in the proposed framework, it is necessary to recognize that blockchain technology still presents different challenges and constraints at the technological level in the examined industries and empirical context of RSC.

Future work should first test the feasibility of applying the proposed framework and then transform it into a software system. More specifically, to validate the proposed framework, the authors plan to begin by identifying the core structure of the DPP use case. This is followed by developing a reference technical architecture for the integration of DPP and blockchain. Subsequently, system dynamics will be applied to assess its potential impact and feasibility, before proceeding to establish an information system.

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# Integrating blockchain with digital product passports for managing reverse supply chain

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