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Integrating blockchain with digital product passports for managing reverse supply chain

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ABSTRACT

The evolution of the circular economy has led to the adoption of circular supply chains, where efficient management of the reverse supply chain enhances resource utilization, minimizes waste, and fosters a circular supply chain. However, managing reverse supply chains presents numerous challenges including a lack of information transparency and traceability, inconsistent cooperation among stakeholders, and uncertainty in recycling process, such as variations in quantity, quality, and timing. To address these challenges, an information sharing framework that integrates blockchain technology with digital product passports (DPPs) is designed to manage reverse supply chain information. Subsequently, a system dynamics model is applied to evaluate the potential impacts and feasibility of this framework within the reverse supply chain and its implications for the forward supply chain. The results indicate that the application of the proposed framework enhance the legal recycling market, reduces the negative environmental impact of illegal recycling activities, mitigates the bullwhip effect within the forward supply chain, and improves market fulfillment rate. The proposed information sharing framework can be employed to enhance the information efficiency of the reverse supply chain, aid in the recovery of end-of-life products and critical resources utilization, thereby supporting the transition to a circular economy.

1. Introduction

The traditional “take-make-dispose” model prevalent in today’s linear economy leads to escalating resource consumption, which is unsustainable in the long run (Neves and Marques, 2022). For instance, the transition to e-mobility within the European Union (EU) is projected to increase the demand for critical materials like lithium by 60-fold, cobalt by 15-fold, and other rare earth elements by 10-fold by 2025 (European Commission, 2021). To address this, governments worldwide are adopting circular economy strategies aimed at decoupling economic growth from resource consumption. Examples include the EU’s new Circular Economy Action Plan (European Commission, 2020a), China’s 14th Five-Year Plan for Circular Economy Development (ADB, 2021), Japan’s Circular Economy Vision 2020 (METI, 2020), and the U.S. Federal Consortium for Advanced Batteries established by the U.S. Department of Energy (USDoE,

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2020). However, a critical implementation barrier remains: the lack of transparency in data sharing and the absence of standardized data and processes significantly hinder efforts to scale up the circular economy (Walden et al., 2021).

The advancement of the circular economy has accelerated the shift towards circular supply chains. Effective management of these chains, particularly the reverse supply chain, is essential for mitigating issues such as escalating waste, pollution, and the depletion of scarce resources (Tseng et al., 2022). The reverse supply chain focuses on recovering components and end-of-life products from consumers, reintegrating them into production cycles through recycling, reprocessing, remanufacturing, and reuse (Xia et al., 2022). Efficient management of the reverse supply chain enhances resource utilization, minimizes waste, and reinforces the circular supply chain (Xia et al., 2024a). However, this process involves complex operations and multiple stakeholders, leading to challenges such as unclear responsibility, and human error (Kalverkamp and Young, 2019), lack of transparency (Zhang et al., 2023a), inconsistent stakeholders cooperation (Bianchini et al., 2019), and uncertainties in the recycling process (Xia et al., 2023a).

In response to these complex challenges, digital product passports (DPPs) and blockchain technology have emerged as transformative tools capable of revolutionizing global information sharing (Walden et al., 2021). DPPs, as digital solutions for identification and tracking, encapsulate detailed product lifecycle information in a standardized and comparable format (King et al., 2023). This accessibility enables all actors across the value and supply chains to make well-informed decisions regarding recycling, reprocessing, and remanufacturing, thereby reducing reliance on primary materials (Adisorn et al., 2021). Moreover, the European Commission has underscored the importance of DPPs in enhancing product durability, reusability, upgradability, and reparability, aiming to bolster maintenance and refurbishment processes (European Commission, 2020b; Nowacki et al., 2023). By providing essential data, including a product's origin, composition, durability, and dismantling options (Adisorn et al., 2021), DPPs play a crucial role in designing products that are easier to repair, upgrade, or recycle, ultimately advancing circular design and sustainability principles (Berger et al., 2023; Saari et al., 2022). However, the implementation of DPPs may encounter significant information security challenges, including the risk of data duplication and alteration within IT systems (Jensen et al., 2023), the absence of robust verification mechanisms (Wu et al., 2023), insufficient security for accessing DPP data (Koppelaar et al., 2023), and the difficulty of effectively linking the physical product with its corresponding digital record (Davies et al., 2024).

While the EU Circular Economy Action Plan advocates for DPP adoption, it notably refrains from prescribing specific technological architectures, leaving implementation choices to market actors (European Commission, 2020a). This policy stance presents a critical integration opportunity, namely blockchain technology can play a pivotal role in addressing the information security risks inherent in DPP ecosystems. Blockchain enhances DPP functionality by fostering trust in a decentralized manner, enhancing transaction transparency and traceability, and ensuring data integrity through its immutable nature (Nofer et al., 2017). By decentralizing data management, blockchain reduces reliance on central authorities, thereby enhancing security and minimizing dependency on third parties (Bhari and Quraishi, 2022; Chowdhury et al., 2018). Furthermore, employing blockchain provides a secure and tamper-proof platform for recording the entire process of value chain transfers and verifying transactions (Meier et al., 2023). Its immutability and transparency help mitigate common issues in reverse logistics, such as information asymmetry and counterfeit products, thus supporting a more trustworthy and efficient circular supply chain (Kudryashov et al., 2020). This advantage is particularly valuable in reverse supply chains, where multiple parties must cooperate without inherent trust in one another.

The integration between these technologies emerges from their complementary capabilities. Blockchain's decentralized trust infrastructure (Nofer et al., 2017) secures DPP data flows, while DPP's standardized content (Adisorn et al., 2021) enriches blockchain's operational value. However, the application of this integration in reverse supply chains for end-of-life product recycling is still emerging. This research addresses the gap by exploring the following research questions: (1) How can blockchain and DPPs be integrated to overcome potential challenges in reverse supply chains? (2) What impacts does this integration have on reverse supply chain specifically the interactions between legal and illegal recycling markets and environmental impacts, and what are its effects on the forward supply chain, particularly with respect to the bullwhip effect and customer satisfaction?

To address the proposed research questions, the aim of this research is to design an information sharing framework that integrates blockchain technology with DPPs for managing reverse supply chain information. This preliminary framework serves as a foundational step for evaluating the integration of blockchain and DPPs before progressing to the design and implementation of a functional information system designed to both enhance reverse supply chain performance and feed critical insights back into forward operations. More specifically, the framework includes the core structure of the DPP use case along with a reference technical architecture for integrating DPPs and blockchain. Subsequently, a system dynamics model is applied to assess the potential impacts and feasibility of such framework within the reverse supply chain and its implications for the forward supply chain. While reverse supply chain operations are the initial focus, these impacts inevitably propagate across the entire closed-loop supply chain, affecting forward supply chain decisions and overall circularity. The proposed framework is intended to serve as a universal reference for the broader adoption of reverse supply chain information management, thereby enabling efficient reverse supply chain process management and facilitating sustainable circular economy objectives across the entire closed-loop supply chain.

The rest of the paper is structured as follows. A comprehensive literature review, focusing on the DPPs, blockchain technology, their integration within reverse supply chains, and the application of system dynamics in supply chain analysis, is presented in Section 2. In Section 3, the proposed information sharing framework and the system dynamics model are illustrated. The case study is detailed in Section 4. An in-depth analysis of the results is discussed in Section 5. Lastly, Section 6 draws a conclusion and highlights future research.

2. Literature review

In this section, relevant research on DPPs, the application of blockchain technology in reverse supply chains, the integration of

DPPs and blockchain for reverse supply chain management, and the use of system dynamics in supply chain analysis are reviewed.

2.1. Digital product passports (DPPs)

The convergence of regulation proposals and material scarcity drives DPP development. For example, Regulation (EU) 2023/1542 introduces a “battery passport” that includes data fields such as cobalt supply chain due diligence and carbon footprint, with full implementation scheduled for 2027 (European Commission, 2023). Additionally, the proposed EU Eco-design for Sustainable Products Regulation (ESPR) requires products to disclose sustainability information, covering aspects such as durability, modular design, and standardized repairability metrics, with specific criteria to be defined for each product category (European Commission, 2022). DPPs serve as the technological backbone for compliance by digitally encapsulating these regulatory parameters throughout product life cycles, thereby offering substantial opportunities for advancing circular economy objectives (King et al., 2023). In line with these regulation proposals, DPPs systematically encodes critical parameters and product data, including origin, material composition (e.g., hazardous substance thresholds), durability, modular design schematics, maintenance history, repair guidelines, and dismantling options, in a standardized and comparable format (Xia et al., 2025).

Researchers have proposed DPP applications across various fields. For instance, a cross-jurisdictional waste trading method using DPPs is suggested (Wu et al., 2023). Further, a conceptual framework for a circular supply management system is presented, utilizing DPPs to recover critical raw materials at both component and material levels, thereby promoting reuse and recycling (Koppelaar et al., 2023). Compared to traditional enterprise IT innovations, such as Enterprise Resource Planning (ERP) and Product Lifecycle Management (PLM)), DPPs offers several distinctive advantages in managing product lifecycle data, particularly crucial for effective reverse supply chain operations. Firstly, traditional systems like ERP and PLM typically operate within organizational boundaries and rely on centralized data management, which leads to data fragmentation, inconsistent data sharing across organizations, and restricted visibility. In contrast, DPPs enable continuous and standardized data sharing across the entire supply chain (Adisorn et al., 2021), thereby transcending organizational silos and fostering comprehensive seamless reverse logistics processes such as product returns, remanufacturing, and recycling. Secondly, ERP and PLM systems tend to be rigid, often requiring substantial customization or redevelopment whenever regulations, standards, or sustainability criteria change. This inflexibility results in delayed adaptation and increased operational costs in reverse supply chains. Conversely, DPPs exhibit inherent flexibility, allowing for automatic updates of product data to align with evolving regulatory requirements or sustainability standards without the need for extensive system overhauls (Nowacki et al., 2023), thus ensuring continuous regulatory compliance and efficient reverse supply chain adaptation. Thirdly, while ERP and PLM systems are primarily designed on enhance internal efficiency and productivity, they often lack comprehensive sustainability tracking capabilities. They typically record only static data points without real-time environmental monitoring or complete lifecycle data integration. Such limitations restrict their applicability in reverse supply chain scenarios where product condition assessment, detailed lifecycle histories, and environmental impact tracking are vital for making timely reuse, recycling, or disposal decisions. DPPs, on the other hand, can advance sustainability tracking by capturing real-time lifecycle data, enabling reverse supply chain stakeholders to effectively evaluate product condition, accurately identify components suitable for reuse or refurbishment, and effectively recover critical materials, thereby reducing environmental impacts and operational costs (Berger et al., 2023).

In reverse supply chain management, both researchers and industry stakeholders are exploring DPP benefits. One conceptual supply management system employs DPPs for critical raw materials recovery; in this design, the DPP functions as a universal product identifier, facilitating seamless information exchange via a dedicated web portal (Koppelaar et al., 2023). Moreover, adopting DPPs can enhance the value recovery of reused and remanufactured products (Kumar and Chopra, 2023). For instance, in automotive industry, companies like Renault and Daimler have launched second-life battery projects. A digital battery passport can significantly support these initiatives by logging each battery’s usage history, health data (e.g., cycles, capacity), and providing disassembly instructions (CIRPASS Project, 2024). This detailed information enables second-life operators to promptly assess which batteries are fit for reuse and safe refurbishment, while also assisting recyclers in understating battery chemistry and components, thereby reducing costly testing, improving worker safety during disassembly, and enhancing the recovery of critical material (e.g., cobalt, nickel, lithium). In the building sector, the BAMB (2020) proposal, developed through collaboration among partners from seven countries, integrates DPPs, innovative business models, and policy agendas to advance circular economy implementation. By emphasizing material characteristics and the potential for recovery and reuse, DPPs help determine the market value of used building materials (BAMB, 2020). Similarly, in e-waste sector, the “waste electrical and electronic equipment (WEEE) passport” concept allows a recycling operator to scan an end-of-life product’s DPP and instantly access information on how to safely remove the battery or identify parts containing high-value metals (CIRPASS Project, 2024). This capability increases the recovery of precious metals and reduces the pollution risk associated with e-waste processing.

However, addressing information security challenges is crucial in DPP implementations. One major concern is the potential for data duplication and alteration within IT systems, which raises questions about the authenticity and reliability of the recorded information (Jensen et al., 2023). Ensuring data integrity and regulatory compliance is critical for maintaining stakeholders trust throughout the value chain (Xia et al., 2024b). Without robust verification mechanisms, unauthorized modifications or inconsistencies in product records could lead to inefficiencies, compromise regulatory compliance, and foster mistrust among participants, thereby hindering the effective implementation of DPPs in managing reverse supply chains (Wu et al., 2023). Additionally, securing access to DPP data is essential to prevent unauthorized parties from tampering with or exploiting sensitive product information, as any breach or data manipulation could disrupt resource recovery processes and undermine overall sustainability objectives (Koppelaar et al., 2023). Furthermore, effectively linking the physical product to its digital DPP record remains a critical challenge (Davies et al., 2024), especially in reverse supply chains where product authenticity significantly impacts recycling or remanufacturing processes. Without a secure and reliable method to connect physical items to their digital counterparts, the potential for fraud and errors increases, potentially compromising the entire process across reverse supply chains.

2.2. Application of blockchain technology in reverse supply chain

Blockchain technology, first introduced in the Bitcoin white paper (Nakamoto, 2008), is a distributed ledger technology that facilitates peer-to-peer (P2P) transactions among untrusted nodes through a decentralized network (Berdik et al., 2021). Its core features include decentralization, transparency, immutability, irreversibility, smart contract automation, and consensus mechanisms (Dutta et al., 2020). Compared to traditional IT solutions, such as centralized databases, barcode systems, and cloud computing, blockchain offers distinctive advantages in managing supply chain information. Firstly, while centralized databases efficiently handle large datasets within a single organization, they inherently rely on a trusted central authority. This reliance creates vulnerability points susceptible to data manipulation, unauthorized access, and potential fraud. Such weaknesses become particularly problematic in reverse supply chains, where multiple stakeholders often lack mutual trust and transparency is critical. In contrast, blockchain's decentralized structure distributes information across multiple nodes, thereby eliminating these risks by distributing data across multiple nodes, thus ensuring transparency and eliminating single points of failure (Chowdhury et al., 2018). This feature enables all reverse supply chain participants to access verifiable, real-time data, substantially improving trust and cooperation. Secondly, although barcode-based tracking technologies enhance visibility and operational efficiency by recording product movements, they do not guarantee data immutability or authenticity, leaving systems susceptible to counterfeiting and fraudulent modifications. This limitation significantly affects reverse supply chain, where verifying the authenticity and provenance of returned or end-of-life products is vital to prevent counterfeiting and fraud. Blockchain overcomes these limitations by providing inherent data immutability through cryptographic hashing and consensus mechanisms (Kshetri, 2018), creating tamper-proof records that ensure reliable verification of products' origins, conditions, and transaction histories throughout the reverse supply chain. Thirdly, cloud computing facilitates scalable and cost-effective data sharing among supply chain participants, yet it often relies on centralized servers managed by third-party providers. This dependency introduces potential risks related to data confidentiality, security breaches, and service availability, issues particularly problematic in reverse supply chains where stakeholders require continuous, secure, and trustworthy access to detailed historical product data. Blockchain reduces third-party dependencies by enabling secure, decentralized data management (Bhari and Quraishi, 2022), which allows stakeholders to maintain direct control over their data, improve information security, and ensure high transparency throughout reverse supply chain operations. Blockchain has demonstrated its advantages across various industries, including financial services (Ali et al., 2020), agriculture (Cao et al., 2022), the food sector (Behnke and Janssen, 2020; Zhang et al., 2023b), the automotive sector (Nizamuddin and Abugabah, 2021), healthcare (Farouk et al., 2020), manufacturing (Khanfar et al., 2021), shipping (Papathanasiou et al., 2020), education (Atienza-Mendez and Bayyou, 2019), aviation (Ahmad et al., 2021), and renewable energy (Juszczyk and Shahzad, 2022).

Supply chain management serves as the backbone of every industry (Hughes et al., 2019) and broadly encompasses sectors that have widely adopted blockchain technology, particularly in the forward supply chain. This application has been explored in various studies (Agrawal et al., 2023; Dutta et al., 2020; Helo and Hao, 2019; Kshetri, 2021; Pournader et al., 2020). However, the reverse supply chain, a crucial component of supply chain management, encounters significant challenges regarding transparency, traceability, trust, and efficient information sharing. Specifically, a lack of transparency and traceability often results in difficulties accessing accurate and comprehensive data about the material lifecycles, leading to information asymmetry that affects verification processes and trust (Zhang et al., 2023a). Inconsistencies in the information flow about resources, products, and processes not only raise consumer safety concerns, but also diminish enthusiasm for recycling (Bianchini et al., 2019). Moreover, the varied goals and strategies of stakeholders lead to inconsistent information flow and cooperation, complicating the alignment of operations across the reverse supply chain, which undermines trust and destabilizes collaboration. Additionally, the unpredictability in the reverse supply chain, such as variations in quantity, quality, and timing, further complicates production planning and control, presenting challenges for stakeholders in making well-informed decisions (Xia et al., 2023b).

Scholars and industry stakeholders have explored blockchain technology's potential to address these challenges. As an example, an integrated triple retry framework is proposed for circular blockchain platforms in the reverse supply chain (Centobelli et al., 2022). In product recall management, the Ethereum blockchain, integrated with the Interplanetary File System, handles large data volumes in the automotive industry (Patro et al., 2021). For end-of-life products management, a smart contract-based architecture is developed for recycling mobile phones (Dasaklis et al., 2020). A blockchain-based solid waste management model is built to enhance efficiency and an optimization model for waste trade among entities (Gopalakrishnan et al., 2021). Integrating the reverse supply chain to manage upstream and downstream participants can reduce value chain costs and uncertainty, ultimately delivering maximum value to customers (Jraisat et al., 2023). In practice, by leveraging a tamper-proof, shared ledger and automating processes via smart contracts, blockchain helps companies reclaim value from returned goods, ensure sustainable practices, and build trust with consumers and partners in ways that traditional systems could not achieve. For instance, the Plastic Bank rewards local collectors with digital tokens (recorded on an IBM's blockchain platform) for each batch of ocean-bound plastic collected, and manufacturers can trace this recycled "social plastic" back into new products, assuring brand partners that the material they use is authentically recycled and ethically sourced (Plastic Bank, 2024). Moreover, specific deployments in the automative sector are still in the early stages, where blockchain is being tested to ensure that returned or aftermarket parts are authentic, helping verify if the part is still under warranty and if it can be refurbished, as well as preventing counterfeit parts from being introduced as "returns" (Talk Business & Politics, 2018). Further, Sims Lifecycle Services, a major electronics recycler, describes how certificates of destruction for sensitive electronics can be secured on a blockchain to prevent fraud, giving customers peace of mind that their data-bearing devices are truly destroyed and nor resold illicitly

(Rohi Sukhia, 2019).

In summary, blockchain technology has the potential to address challenges in the reverse supply chain. The blockchain platform often serves as a trust-based network for sharing and validating information among various parties (Hawlitschek et al., 2018). However, its application in reverse supply chains, particularly for end-of-life product recycling, is still emerging. In addition, as a technological framework, blockchain technology primarily emphasizes data storage and security rather than the specifics of data content, leading to limitations in tracking the lifecycle of returned products and presenting detailed data content (Subramanian et al., 2020).

2.3. Integration of DPPs and blockchain technology in reverse supply chain

Integrating DPPs with blockchain technology offers a promising solution to overcome the inherent limitations of DPP systems. For example, in asset management, blockchain-based product passports ensures quality compliance, identify counterfeit products, and enhance overall product and service safety, thereby bolstering project managers' confidence in using high-quality materials (Sadeghi et al., 2023). Similarly, implementing blockchain to maintain solar passports underscores the need for systematic quality control and registration processes, ensuring that the information remains current (Kumar and Chopra, 2023). In the electric vehicle battery supply chain, the combined use of blockchain and DPPs supports circular economy requirements by focusing on effective battery tracking and capability sharing (da Silva et al., 2023).

This integration also offers distinct advantages over previous traditional IT solutions, such as centralized databases with tracking technologies and ERP systems with cloud platforms. Although centralized databases enhanced by tracking tools (e.g., barcodes) provide a reliable means of product identification and movement tracking, their centralized architecture depends heavily on a single authority for data storage and security. This reliance creates vulnerabilities, such as single points of failure, susceptibility to data manipulation, and risks of inconsistent data updates (Chowdhury et al., 2018). Similarly, while ERP systems combined with cloud platforms enable data sharing and visibility among supply chain stakeholders, this approach still relies on a host organization or third-party provider to ensure data security, accuracy, and timeliness (Alsharari et al., 2020). Such dependency can lead to delays, disputes, and trust issues when stakeholders encounter missing or conflicting data.

Conversely, by integrating DPPs and blockchain, blockchain's immutable and decentralized architecture ensures robust verification, prevents unauthorized data alteration, and enhances data integrity, directly mitigating security and trust concerns (da Silva et al., 2023). Additionally, blockchain's cryptographic protocols secure DPP data access, significantly reducing risks related to unauthorized manipulation or exploitation and mitigating reliance on any single entity for data accuracy and security (Iansiti and Lakhani, 2017). Furthermore, blockchain's traceability features combined with standardized DPP protocols, thus establishing a reliable and tamper-proof connection between physical items and their corresponding digital information (Sadeghi et al., 2023). Moreover, blockchain's smart contracts automate verification processes, minimize human errors, reduce potential conflicts, and streamline cooperation among stakeholders (Tezel et al., 2021). It can be concluded that blockchain is particularly well-suited for enhancing DPP functionality. This integration creates a dual-layer assurance mechanism: DPP structures the "what" of product data (e.g., material specifications, maintenance history), while blockchain authenticates the "how" of data transactions (e.g., transfer timelines, stakeholder interactions). This dual-layer assurance mechanism enhances trust, transparency, and traceability in reverse supply chains, essential for managing product lifecycle data, ensuring compliance with regulatory standards, and improving operational efficiency. This integration promises to improve the recovery of product and material value while mitigating risks in data exchange and reducing losses from counterfeit products (Kudryashov et al., 2020; Meier et al., 2023).

The integration of DPPs and blockchain in reverse supply chain has attracted significant attraction from both scholars and industry stakeholders. For instance, a sustainable plastic waste management method is introduced by combining DPPs with blockchain technology (Bhubalan et al., 2022). Furthermore, a novel conceptual framework that integrates DPPs and blockchain is proposed to manage reverse supply chain for circular economy practices (Xia et al., 2025). Moreover, a resources passport, acting as a digital twin and consolidating data on a blockchain platform, facilitates communication with various identification systems (Excess Materials Exchange, 2019). In practice, the Global Battery Alliance, a consortium including automobile manufacturers, is piloting a Battery Passport prototype using blockchain to track batteries from production to second-life reuse and recycling (Recycling Product News, 2024). In this system, the DPP can be scanned to reveal details such as remaining capacity, chemistry, and ownership history once an EV battery is retired. Beyond batteries, carmakers such as Bavarian Motor Works (BMW) have piloted blockchain to trace auto parts auto parts across suppliers, aiming for complete components traceability. This level of traceability means that if a defect is detected, only the affected batch is recalled, with each returned part's path thoroughly documented to reduce waste (FreightWaves, 2020). Another notable use case involves a prototype solution for electronic devices developed by the IOTA Foundation in collaboration with industry partners (Lawrence Jengar, 2024). In this system, each device (e.g., a laptop or smartphone) receives a digital passport on a distributed ledger at the point of manufacture, with stakeholders updating it throughout the product's lifecycle. In the IOTA pilot, a recycler scans the device and marks it as e-waste, recording proof of recycling on the blockchain. This record can then be verified by auditors via the DPP, addressing uncertainties about whether products are truly recycled or simply end up in landfills. By ensuring data integrity and traceability from manufacturing to recycling, this approach not only aids in compliance verification with recycling mandates but also instills confidence among consumers, recyclers, and regulators in the electronics reverse supply chain.

In summary, by creating an immutable ledger of product data, blockchain technology prevents unauthorized modifications and secures the link between physical products and their digital records. The integration of DPPs and blockchain can serve as a powerful tool to establish an information sharing framework that supports efficient data exchange and collaborative practices within the reverse supply chain. Although this technological convergence has the potential to address core challenges in reverse supply chain management, it may also introduce new system complexities and dynamic challenges in practical applications. For example, real-time product information updates and multi-stakeholder interactions can generate complex feedback mechanisms with unpredictable knock-on effects. Therefore, to thoroughly analyze and understand the impact of integrating DPPs and blockchain in reverse supply chains, it is essential to adopt appropriate modeling tools, such as system dynamics, to systematically capture these dynamic processes.

2.4. Application of system dynamics to supply chain

Simulation models used to evaluate supply chain performance primarily include three categories: agent-based simulation, discrete-event simulation, and system dynamic models. Agent-based simulation models focus on modeling the behaviors and interactions of individual actors (Lohmer et al., 2020), requiring micro-level data to calibrate decision rules (Cammarano et al., 2023). Discrete-event simulation tracks system state changes at specific event times and is widely applied for operational and process-level analyses; however, it is less suited to exploring the long-term, system-wide feedback effects introduced by novel technologies such as integration of blockchain and DPPs (Tako and Robinson, 2012). In contrast, system dynamics captures the overall trends and systemic patterns of a system. System dynamics is particularly effective at studying macro-level dynamics of complex systems by simulating feedback loops and time delays. This approach is especially valuable when detailed micro-level data is limited or confidential, as it requires less granular data to generate meaningful insights. Thus, system dynamics is better suited for early-stage research, such as in the initial development of the DPPs, where comprehensive data may not yet be available.

System dynamics, introduced by Forrester in 1968 (Forrester, 1997), leverages feedback loops and the informational structure within a system to develop models that analyze dynamic changes and predict the outcomes of various strategy (Swanson, 2002). It is widely used across various fields (Azar, 2012), especially in supply chain management. For example, it has been applied to optimize humanitarian supply chain deliveries, enhancing tracking capabilities and trust among stakeholders to improve coordination and synergy (Izadi et al., 2023). In reverse food supply chains, system dynamics has been employed to simulate and predict greenhouse gas emissions, demonstrating how reverse logistics can bolster green performance management by reducing food waste (Kazancoglu et al., 2021). In practice, a system dynamics model for analyzing the reverse supply chain of electric vehicle batteries is developed, studying circular economy transitions by examining how used EV batteries are collected, remanufactured or recycled, and how the system evolves over time (Alamerew and Brissaud, 2020). Similarly, a recent system dynamics study explores WEEE reverse supply chain in China, examining strategies to mitigate risks associated with electronic recycling, such as environmental hazards and informal recycling practices (Zheng et al., 2022). The model tested various combinations of government strategies to predict resulting risk levels.

System dynamics, a methodology designed to tackle complex and dynamic problems (Sterman, 2001), is especially useful when new technologies introduce unique challenges. It has been used to assess blockchain's impact across various supply chains. For example, system dynamics is used to examine the behavior of the blockchain acceptance rate in Iran's flexible home appliances supply chain, helping to define the non-linear relationships between the model's variables (Roozkhosh et al., 2023). In addition, it is employed to map milk supply chains to enhance information flow and traceability, as well as to assess the societal impacts of blockchain technology in fostering social sustainability within the milk supply chain (Mangla et al., 2021). Similarly, blockchain-based tokenization is proposed as an alternative incentive system, with its effects on plastic bottle supply chains investigated through system dynamics (Wankmüller et al., 2023). Moreover, a blockchain-based information sharing system integrated with system dynamics simulation is developed to reduce costs, improve supply chain management quality, and enhance the overall system efficiency (Xue et al., 2021).

In summary, system dynamics provides an effective framework for capturing and analyzing feedback loops, time delays, and nonlinear relationships inherent in supply chain systems (Wu and Yan, 2009), especially those incorporating emerging technologies like blockchain and DPPs. Its capacity to simulate feedback mechanisms and time-dependent behaviors helps researchers and practitioners better understand how these technological integrations could impact both reverse and forward supply chain processes. Therefore, system dynamics is used to assess the potential impacts and feasibility of the proposed information sharing framework for managing the reverse supply chain, offering a robust method for evaluating the complex challenges introduced by new technologies in supply chain management.

2.5. Research gaps

While the literature on DPPs, blockchain technology, their integration, and system dynamics in supply chain management is extensive, several key gaps remain, especially regarding their integrated application in reverse supply chains. Although DPPs have been proposed as a solution for enhancing lifecycle data continuity, regulatory adaptability, and sustainability tracking, most existing studies focus on isolated technical or conceptual benefits (Adisorn et al., 2021; Berger et al., 2023; Nowacki et al., 2023; Xia et al., 2025). Empirical evidence is limited regarding how DPPs perform in practical settings, particularly in managing the complexities of reverse logistics for end-of-life product recycling.

Similarly, while blockchain technology has demonstrated its advantages in ensuring data immutability, decentralized trust, and traceability, its application in reverse supply chains, especially in the context of remanufacturing and waste management, remains in its infancy (Chowdhury et al., 2018; da Silva et al., 2023). Moreover, blockchain's strength in securing data does not naturally extend to managing product information details, such as material composition, repair history, and end-of-life handling instructions, which are crucial for effective reverse supply chain operations (Subramanian et al., 2020).

Despite the theoretical advantages of combining DPPs with blockchain, such as enhanced security, traceability, and data integrity

(Sadeghi et al., 2023), there is a notable lack of empirical studies demonstrating the practical implementation and effectiveness of this integration in real-world reverse supply chains. Current literature often discusses DPPs and blockchain separately or in conceptual terms, with few detailed use cases or analyses of their combined operational challenges and benefits in industries where reverse supply chains are crucial, such as automotive and electronics.

Furthermore, although system dynamics has been effectively used to simulate supply chain performance and evaluate policy impacts, few studies that apply system dynamics modeling specifically to integrated DPP-blockchain frameworks in reverse supply chains (Mangla et al., 2021; Roozkhosh et al., 2023). Most system dynamics applications have traditionally focused on forward logistics and aggregate sustainability assessments, rather than on the intricate dynamics of reverse supply chains, where linking physical products to their digital passports in real time is essential.

Specifically, from a theoretical perspective, integrating blockchain and DPPs within a comprehensive framework provides new insights into overcoming persistent reverse logistics challenges. Practically, addressing these gaps can lead to better-designed systems that improve stakeholder collaboration, data transparency, and product lifecycle management efficiency, thus directly supporting broader circular economy goals.

3. Methodology

In this research, a framework for information sharing that combines DPPs and blockchain is proposed. This preliminary framework serves as a foundational step to evaluate the integration of blockchain and DPPs before advancing to the design and implementation of a functional information system. A system dynamics model is then applied to evaluate this conceptual framework's potential impacts and feasibility in managing the reverse supply chain. More specifically, given the development of DPP is still in its infancy (Jansen et al., 2022), the process begins by identifying the core structure of the DPP use case, followed by developing a reference technical architecture for integrating DPPs and blockchain. Although the proposed information sharing framework fully considers data from the forward supply chain, this is essential as it establishes the foundation for managing the reverse supply chain information.

3.1. Information sharing framework

3.1.1. DPP use case framework

The DPP use case framework is developed following the steps illustrated in the research by Nowacki et al. (2023). Inspired by the stakeholder-specific functions and requirements identified by King et al. (2023), the core content of DPPs for each stakeholder group is identified across both forward and reverse supply chains (see Fig. 1). More specifically, the blue sections represent the forward supply chain, while the green sections depict the reverse supply chain. As the integration of DPP increases, the color intensity deepens,

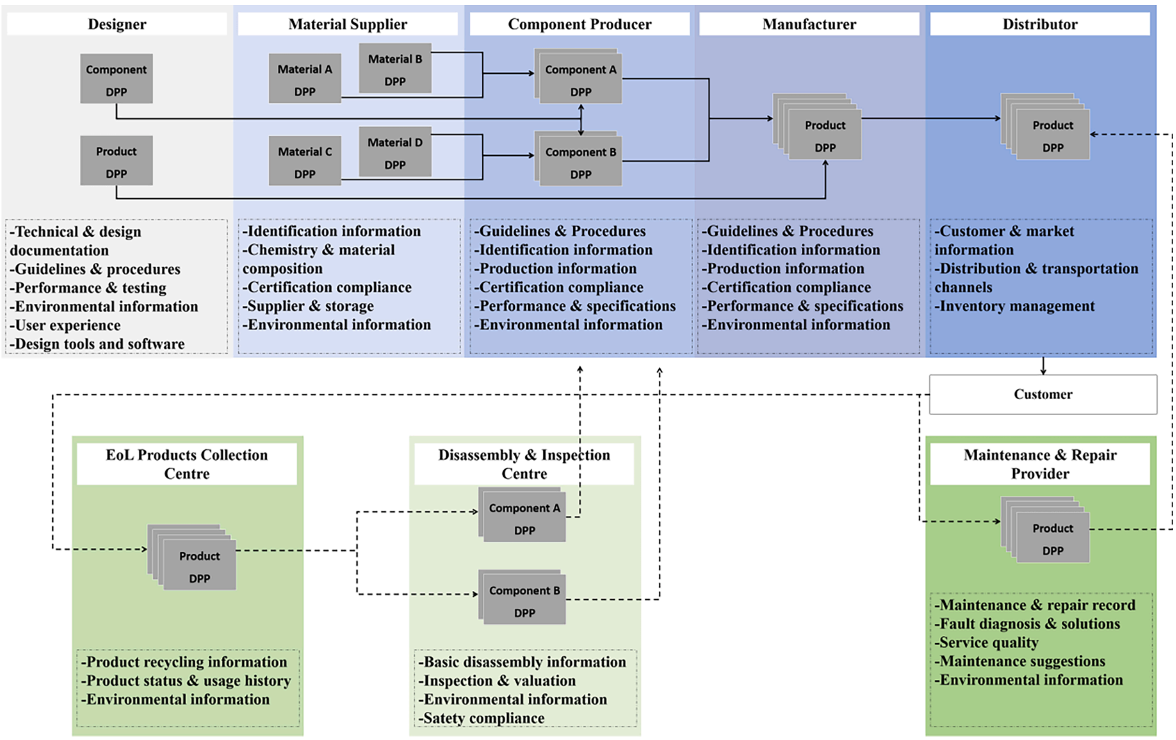


Fig. 1. Reference framework for DPP use case across various stakeholders.

symbolizing more extensive utilization and information depth within each segment of the supply chain. Recognizing that the forward supply chain forms the foundation for managing reverse supply chain information, the upper section of the use case framework is designed to capture persistent DPP data at various stages within the forward supply chain prior to reaching the consumer. This aids in providing comprehensive information on the lifecycle and production flow. Thus, the whole set of system transactions can be categorized into forward logistics stage and reverse logistics stage. Further, following the DPP classification guidelines from the manufacturing industry provided by Stratmann et al. (2023), the specifics of the reference framework for the DPP use case across various stakeholders are illustrated in Table A2.

More specifically, the use case framework is developed from the design stage, where the DPP for both components and products are created. As materials are supplied, each batch receives a unique DPP, which is then incorporated into the components produced from these materials. These components are also linked to the DPPs generated during the design phase. At the manufacturing level, the final product incorporates the DPPs from its components and design, which is crucial for traceability and verification once the product reaches the distribution stage. Distributors are responsible for ensuring that each product has a unique DPP before it reaches the market, allowing consumers to verify the authenticity of their purchases. For products requiring maintenance and repair, service providers can access detailed information via the DPPs to offer targeted services.

At the end-of-life (EoL) product recycling stage, collection centres are responsible for collecting recycling information on the corresponding DPP, following the recycling guidelines provided by the manufacturer's DPP. Based on the initial information from the collection centres and disassembly instructions in the DPP provided by the designers, component producers, and manufacturers, the recycled EoL products are disassembled into components, which are then repurposed as raw materials for remanufacturing, reuse, or refurbishing. In addition, component-related information, such as damage assessment and current valuation, is documented. The recovery mode for these components, whether remanufactured, reused, or refurbished, is determined, and waste and residual material are managed accordingly. After deciding the recovery mode of the components, and in line with the production plan, these components are shipped back to their producers, re-entering the full life cycle until final disposal. The necessary information about these repurposed recycled components is then extracted and nested into a new component DPP or product DPP.

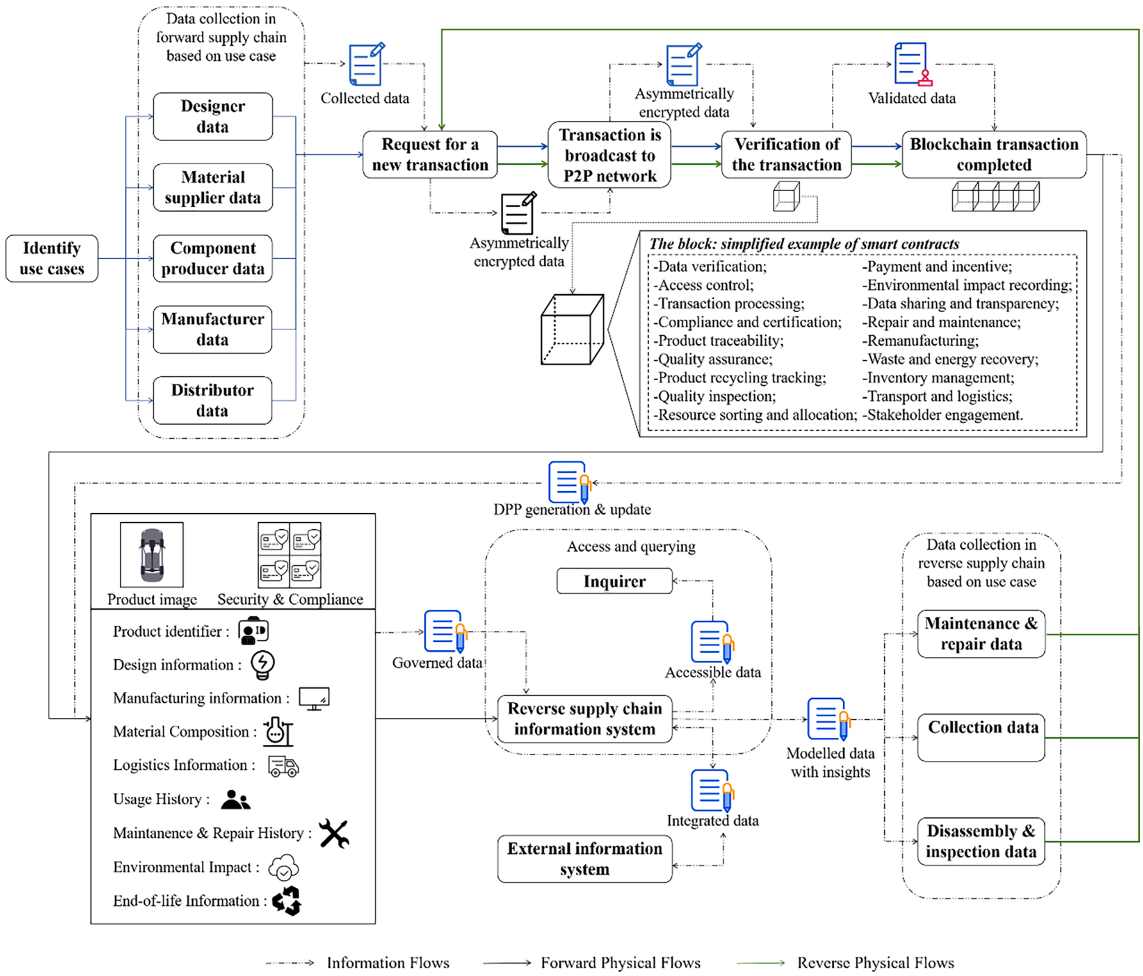


Fig. 2. Technical architecture for integrating DPP and blockchain.

3.1.2. Technical architecture for integration of blockchain with DPP

A technical architecture is proposed to convey seamless information communication, as depicted in Fig. 2. This system collects data from various supply chain stakeholders, which might be captured automatically via Internet of Things (IoT) devices or entered manually. Sensitive data is hashed, and both the hash value and non-sensitive data are recorded on the blockchain. Data from these stakeholders initiate new transactions within the P2P network, broadcast using asymmetric encryption for secure transmission. Other blockchain nodes receive and validate these transactions. Validated transactions are compiled into a new block, confirmed through a specific consensus mechanism. For instance, in the EoL product recycling chain, the validity of recycled data is tested based on a consensus mechanism. Data shared by EoL product recycling enterprises are verified and recorded on the blockchain, preventing any entity from concealing data or information.

Data processing, transaction requests, and verification are automatically managed and updated by smart contracts throughout the process of recording DPP content on the blockchain at each stage. For example, based on identified use cases, contracts like product recycling tracking, inventory management, and remanufacturing management should be established among reverse supply chain operators to standardize and streamline business processes. Subsequently, a new block, timestamped and linked to the previous chain, is added to the blockchain, signifying the completion of the transaction. This transaction data and relevant information are hashed and stored on the blockchain to generate or update a DPP. Compliance with standards, certifications, and regulations is important during the DPP generation and update process. Moreover, external system information can also be integrated with the combined DPP and blockchain information sharing framework across the whole value chain. For example, a leading Chinese automative enterprise connects with its enterprise resource planning (ERP) system and external systems like the international material data system (IMDS, 2001) and national new energy vehicle power battery recycling platform (EVMAM, 2018).

3.2. System dynamics simulation

A system dynamics model is developed in this research to evaluate the potential impacts and feasibility of the proposed information sharing framework. The specific steps involved in developing this model include defining system boundaries and model assumptions, identifying model notations, constructing stock-flow diagrams, and conducting model verification.

3.2.1. System boundaries and model assumptions

In this research, the focus is on the reverse supply chain of a single EoL product, covering the recycling, inspection, disassembly, and remanufacturing stages. Other recycling forms, such as product recalls and business-to-business (B2B) commercial returns are excluded. Notably, recycled and remanufactured product components may re-enter and influence the forward supply chain. As depicted in Fig. 2, the DPP, supported by blockchain technology, securely supports data transparency and mitigates information security risks. To analyze how varying levels of product information transparency, namely DPP disclosure level supported by blockchain, impact both reverse and forward supply chains, a system dynamics model is utilized. The proposed information sharing framework establishes the fundamental system boundaries and assumptions guiding the simulations. Specifically, products reaching the end of their life enter the reverse supply chain, where recyclers collect EoL products. A disassembly and inspection centre then processes these products, after which disassembled EoL components are remanufactured to recover usable value. These components subsequently re-enter the forward supply chain, enabling upstream stakeholders to deliver goods based on downstream businesses orders and ultimately satisfying market demands. The following assumptions underpin the development of the proposed system dynamics model.

(1) As illustrated in Fig. 1, the DPP records complete lifecycle information from design and production to sales, recycling, and remanufacturing; however, stakeholders access to this information varies according to the DPP disclosure level (Koppelaar et al., 2023; Psarommatis and May 2024). Higher disclosure levels increase transparency and enable more comprehensive stakeholder access, and vice versa.
(2) Both illegal and legal channels exist for recycling EoL products (Yu et al., 2020). Products recycled through illegal channels often lack proper environmental and safety treatments during disassembly, leading to emissions of solid and liquid pollutants (Ghulam and Abushammala, 2023). Conversely, legal recycled products undergo appropriate environmental procedures. Inspection times and disassembly rates vary based on product quality and are modeled using specific probability distributions. The implementation of the information sharing framework that integrates DPPs with blockchain significantly impacts recycling rates through both channels.
(3) The remanufacturing ratio of recycled components varies by material and is represented by a probability distribution (Liao et al., 2017). This assumption reflects practical variations observed in remanufacturing processes, as not all materials and components possess equal potential for remanufacturing due to differences in wear, deterioration, technology complexity, and economic viability. By employing probabilistic distributions, the model captures the inherent variability in remanufacturing rates for different components, thus enhancing its applicability to real-world scenarios.
(4) The model assumes no explicit constraints on manufacturing and remanufacturing capacities, recycling abilities, sales potential, or inventory and logistics capabilities among supply chain stakeholders (Xia et al., 2024a). Moreover, no material losses are assumed during the storage and transportation within both reverse and forward supply chains (Ekvall et al., 2020). Although capacity limitations and material losses often exist in real-world operations, the purpose of this assumption is to focus on specifically on the impacts of the proposed information-sharing framework, isolating its benefits without interference from other operational constraints.

Table 1
Model notations.

Stocks		**Referenced units**
$RV_{illegal}$	Illegal recycling volume	Unit
RV_{legal}	Collection centre recycling volume	Unit
DV	Disassembly & inspection centre volume	Unit
$I_{retailer}$	Retailer inventory	Unit
$I_{manufacturer}$	Manufacturer inventory	Unit
$I_{component}$	Component producer inventory	Unit
Flows		
$R_{illegal}$	Illegal recycling rate	Unit/Week
R_{legal}	Legal recycling rate	Unit/Week
$SR_{collection}$	Collection centre shipping rate	Unit/Week
$SR_{disassembly}$	Disassembly & inspection centre shipping rate	Unit/Week
$SR_{manufacturer}$	Manufacturer shipping rate	Unit/Week
$SR_{component}$	Component producer shipping rate	Unit/Week
$RR_{disassembly}$	Disassembly & inspection centre receiving rate	Unit/Week
RR_{parts}	Recycled parts remanufacturing rate	Unit/Week
$PC_{component}$	Component producer production completion rate	Unit/Week
$PC_{manufacturer}$	Manufacturer production completion rate	Unit/Week
$RC_{retailer}$	Retailer receiving rate	Unit/Week
S	Sales rate	Unit/Week
Parameters		
$RV_{illegal\_ini}$	Initial illegal recycling volume	Unit
RV_{legal_ini}	Initial collection centre recycling volume	Unit
DV_{ini}	Initial disassembly & inspection centre volume	Unit
$I_{retailer\_ini}$	Initial retailer inventory	Unit
$I_{manufacturer\_ini}$	Initial manufacturer inventory	Unit
$I_{component\_ini}$	Initial component producer inventory	Unit
DP_{liquid}	Rate of liquid pollutants in illegal dismantling	Kg/Unit
DP_{solid}	Rate of solid pollutants in illegal dismantling	Kg/Unit
$CR_{illegal}$	Current illegal recycling rate	Dmnl
CR_{legal}	Current legal recycling rate	Dmnl
DL	DPP disclosure level	Dmnl
B	Blockchain application	Dmnl
PL	Average product lifetime	Week
SR	Scrap rate	Dmnl
$T_{inspection}$	Inspection time	Dmnl
DR_{normal}	Normal dismantling rate	Dmnl
RD_{part}	Recycled parts remanufacturing delay	Week
RE_{part}	Normal recycled parts remanufacturing ratio	Dmnl
$MA_{component}$	Component producer moving average	Week
$MA_{manufacturer}$	Manufacturer moving average	Week
$MA_{retailer}$	Retailer moving average	Week
$D_{current}$	Current market demand	Unit
$L_{component\_prod}$	Component producer production lead time	Week
$L_{manufacturer\_proc}$	Manufacturer procurement lead time	Week
$L_{retailer\_proc}$	Retailer procurement lead time	Week
$AT_{component}$	Component producer inventory adjustment time	Week
$AT_{manufacturer}$	Manufacturer inventory adjustment time	Week
$AT_{retailer}$	Retailer inventory adjustment time	Week
Auxiliaries		
$DF_{component}$	Component producer demand forecasting	Unit/Week
$DF_{manufacturer}$	Manufacturer demand forecasting	Unit/Week
$DF_{retailer}$	Market demand forecasting	Unit/Week
$O_{manufacturer}$	Manufacturer ordering rate	Unit/Week
$O_{retailer}$	Retailer ordering rate	Unit/Week
$DI_{component}$	Component producer desired inventory	Unit
$DI_{manufacturer}$	Manufacturer desired inventory	Unit
$DI_{retailer}$	Retailer desired inventory	Unit
$PR_{component}$	Component producer production rate	Unit/Week
$IA_{component}$	Component producer inventory adjustment	Unit/Week
$IA_{manufacturer}$	Manufacturer inventory adjustment	Unit/Week
$IA_{retailer}$	Retailer inventory adjustment	Unit/Week
$RS_{component}$	Component producer maximum shipping rate	Unit/Week
$RS_{manufacturer}$	Manufacturer maximum shipping rate	Unit/Week
$RS_{retailer}$	Maximum sales rate	Unit/Week
D	Market demand	Unit/Week
P_{liquid}	Accumulated liquid pollutants	Kg
P_{solid}	Accumulated solid pollutants	Kg

(5) Market demand is assumed to be independent and random, represented by defined probability distribution. This assumption aligns with established practices in supply chain modeling, where demand uncertainty captures real-world complexity and enhances the robustness of planning and forecasting (Fergany, 2016). Moreover, the information sharing framework combining DPP and blockchain influences market demand.

(6) Remanufactured products are assumed to be equivalent in quality to new products, with consumers accepting both equally (Zheng and Wu, 2016). This assumption aligns with the industry's standard definition of remanufacturing (MatsumotoDr and IjomahDr, 2013) and is supported by manufacturing practice, which shows that modern remanufacturing processes can produce components whose quality matches that of new parts (Chen et al., 2019). Behavioral experiments and analytical models likewise indicate no significant difference in consumers' purchase intentions between remanufactured and new products when equal warranties are provided (Jin and Zhou, 2020). Accordingly, the model treats demand for new and remanufactured products symmetrically, allowing the analysis to focus on how the proposed information sharing framework affects reverse supply chain performance.

(7) Without the combined DPP and blockchain information sharing framework, information transmission in the forward supply chain is limited to adjacent nodes. Consequently, upstream enterprises rely solely on first-order exponential smoothing of downstream orders to forecast market demands, lacking integrated inventory information from other stakeholders (Lee et al., 1997b).

(8) The information sharing framework that combines DPPs and blockchain serves as an intermediary to facilitate extensive information flow and collaboration among supply chain participants, enabling comprehensive sharing of inventory levels, market demands, and other critical data (Tang et al., 2022). This assumption represents an idealized but realistic potential of advanced blockchain-based platforms, as demonstrated by recent practical implementations in industries like automotive (Mishra et al., 2024), where comprehensive information sharing has significantly enhanced supply chain efficiency, reduced uncertainty (Tuladhar et al., 2024), and improved overall responsiveness (Xia et al., 2023c). Although achieving full real-time transparency is challenging, this assumption highlights the transformative potential of fully integrated proposed framework.

(9) Actual lead time includes both production and procurement lead times. Production lead time refers to the duration from the commencement of production to product completion, while procurement lead time denotes the period from procurement initiation by supply chain nodes to final goods delivery at warehouses. Both lead times are assumed as random variables following specified probability distribution (Yang et al., 2023).

3.2.2. Model notations

The notations representing stocks, flows, parameters, and auxiliaries in the system dynamic simulation model are illustrated in Table 1. Each parameter's unit is provided as a reference and can be adjusted based on specific industry data and practices.

3.2.3. Stock flow diagram and model Construction

The stock flow diagram (SFD) clearly represents the quantitative processes within the system dynamic simulation model, directly aligning with the objective of evaluating the potential impacts and feasibility of integrating blockchain and DPPs in reverse supply

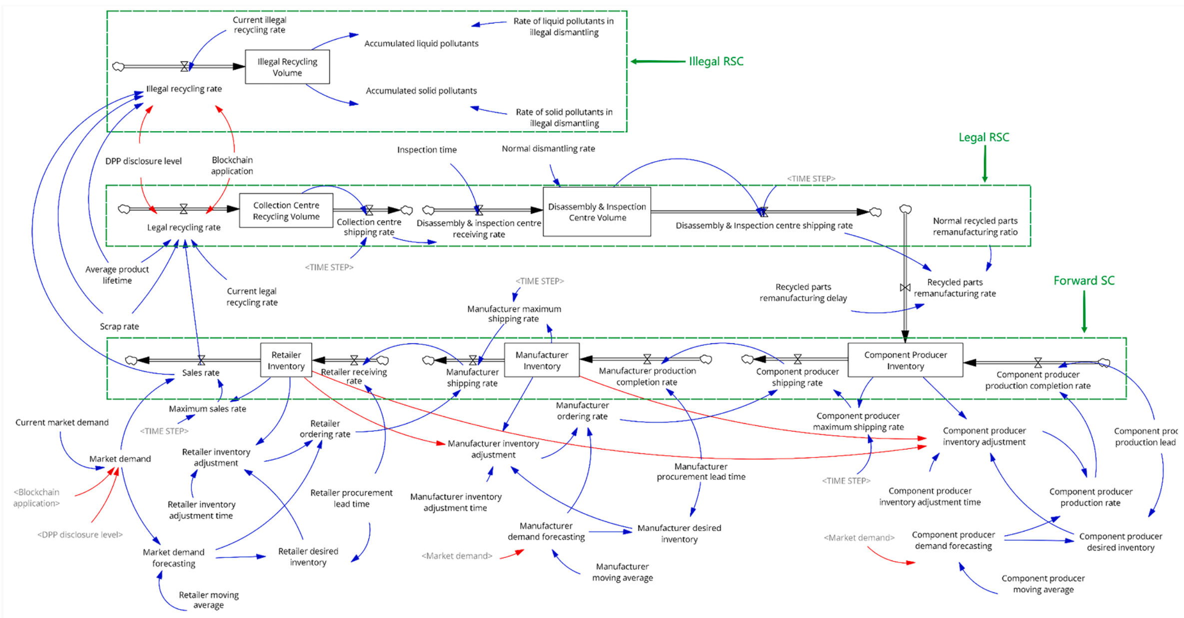


Fig. 3. SFD with the application of information sharing framework combining DPP and blockchain.

chain management. Specifically, the SFD demonstrates how blockchain application and varying DPP disclosure levels influence crucial processes across the entire supply chain, including forward supply chain, legal recycling channels, and illegal recycling channels (as highlighted by the green dashed boxes in Figs. 3 and 4). It illustrates how enhanced transparency and traceability, enabled by the proposed information sharing framework, potentially reduce illegal recycling practices and associated environmental pollutants. This visual representation effectively connects the theoretical model with practical outcomes, providing clarity on how the proposed integration framework can enhance sustainable and efficient reverse supply chain practices.

In this research, the SFDs depict scenarios both with and without the information sharing framework integrating the DPPs and blockchain, as shown in Figs. 3 and 4, respectively. Red arrows within these diagrams highlight the core differences, particularly emphasizing improved market demand forecasting, reduced information delays, and better inventory management resulting from the integration of blockchain and DPPs. The SFD utilizes differential equations to model changes in system state variables over time, thereby simulating the movement of entities within the system. The dynamic interactions between flow and stock variables are clearly illustrated through SFD. Stock variables represent the cumulative amounts, expressed as integrals, which quantify the net inflow by capturing the difference between inflows and outflows, as demonstrated in Eq. (1). Flow variables, which are rate variables, represent the derivative of the stock and are thus depicted in differential form, as shown in Eq. (2). Moreover, the relationship among other model variables can be defined through SFD and utilized to formulate mathematical equations that simulate the model.

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_0) \tag{1}$$

where $Stock(t)$ denotes the stock value at time t, $Inflow(s)$ represents the inflow rate, $Outflow(s)$ indicates the outflow rate, and $Stock(t_0)$ signifies the stock value at the initial time.

$$d(Stock)/dt = Inflow(t) - Outflow(t) \tag{2}$$

Once the SFD for the system dynamics model is constructed, it is essential to logically set the entire model equation. The reverse supply chain system dynamics model initiates from the sales rate. EoL products are modeled as a material delay function of the retailer's sales rate, with the delay corresponding to the product's lifespan. EoL products are recycled by authorized recyclers and subsequently disassembled, inspected, and remanufactured to supply inventory for component producers, thus forming the reverse supply chain segment. The equations related to the recycling, disassembly, and remanufacturing processes through legal channels are illustrated in Eqs. (3)-(9).

$$RV_{legal}(t) = \int_0^t \left(R_{legal}(s) - SR_{collection}(s)\right)ds + RV_{legal\_ini} \tag{3}$$

$$DV(t) = \int_0^t \left(RR_{disassembly}(s) \times DR_{normal} - SR_{disassembly}(s)\right)ds + DV_{ini} \tag{4}$$

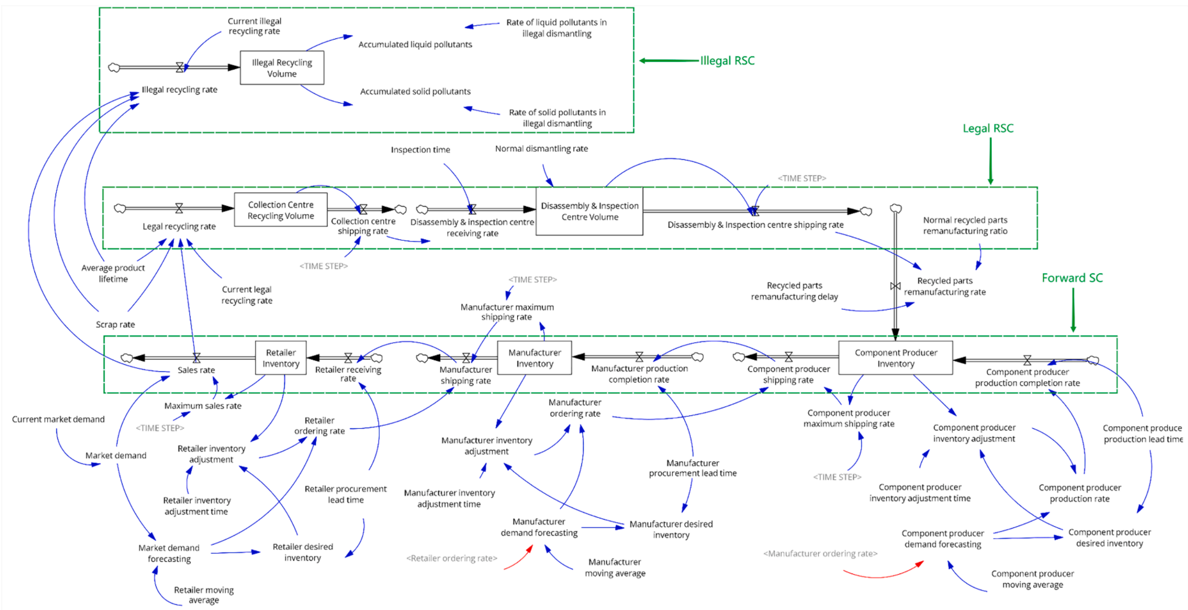


Fig. 4. SFD without the application of information sharing framework combining DPP and blockchain.

Based on the study by Gong et al. (2022), transparent recycling chains enable stakeholders to monitor to the entire process from collection to final remanufacturing, enhancing legal recovery and preventing interventions by middlemen. Therefore, inspired by the studies (De Giovanni et al., 2016; Lin et al., 2024), the legal recycling rate, influenced by both the DPP disclosure level and blockchain, is defined in this research as Eq. (5).

$$R_{legal} = SMOOTH(S, PL) \times SR \times CR_{legal} \times (1 + DL \times (1 - B)) \tag{5}$$

Where $SMOOTH()$ function is a first-order information delay function used to smooth fluctuations in supply changes, productivity inputs, or to model the gradual adoption of new technologies in the market.

$$SR_{collection} = IFTHENELSE\left(RV_{legal} \leq 0, 0, RV_{legal}/TimeStep\right) \tag{6}$$

Where $IF\,THEN\,ELSE()$ function introduces decision logic into the model, allowing it to adopt different behaviors based on various states or conditions. The $Time\,Step$ refers to the interval between two consecutive calculations of the model's state.

$$RR_{disassembly} = DELAY1\left(SR_{collection}, T_{inspection}\right) \tag{7}$$

Where $DELAY1()$ function is a first-order logistical delay function employed to demonstrate the phenomenon of logistical delay.

$$SR_{disassembly} = IFTHENELSE(DV \leq 0, 0, DV/TimeStep) \tag{8}$$

$$RR_{part} = DELAY1\left(SR_{disassembly} \times RE_{part}, RD_{part}\right) \tag{9}$$

Meanwhile, EoL products may also be recycled through illegal channels. The professional level in illegal recycling operations is often low, which makes it challenging to meet environmental standards and leads to environmental pollution, including the release of solid and liquid pollutants. The equations related to the recycling process through illegal channels are presented as Eqs. (10)-(13).

$$RV_{illegal}(t) = \int_0^t \left(R_{illegal}(s)\right) ds + RV_{illegal\_ini} \tag{10}$$

$$P_{liquid} = RV_{illegal} \times DP_{liquid} \tag{11}$$

$$P_{solid} = RV_{illegal} \times DP_{solid} \tag{12}$$

According to Song et al. (2022), transparent supply chains can reduce the information asymmetry between stakeholders within the supply chain and the government, and help combat illegal behaviors. Thus, motivated by the studies (De Giovanni et al., 2016; Lin et al., 2024), the illegal recycling rate, influenced by both the DPP disclosure level and blockchain, is defined in this research as Eq. (13).

$$R_{illegal} = SMOOTH(S, PL) \times SR \times CR_{illegal} \times (1 - DL \times (1 - B)) \tag{13}$$

The forward supply chain system dynamics model begins with market demand. The market demand influences not only the sales rate but also the retailer's market demand forecasting. The retailer place orders with the manufacturer based on its demand forecasts and inventory adjustments. These adjustments are influenced by the retailer's desired inventory, current inventory, and the time it takes to adjust inventory. The equations associated with market demand and retailer's activities are detailed in Eqs. (14)–(22).

$$I_{retailer}(t) = \int_0^t (RC_{retailer}(s) - S(s))ds + I_{retailer\_ini} \tag{14}$$

$$RC_{retailer} = DELAY1\left(SR_{manufacturer}, L_{retailer\_proc}\right) \tag{15}$$

$$S = MIN(D, RS_{retailer}) \tag{16}$$

$$RS_{retailer} = IFTHENELSE(I_{retailer} \leq 0, 0, I_{retailer}/TimeStep) \tag{17}$$

Based on the study by Wang et al. (2021), supply chain transparency improves consumer service and trust, subsequently increasing cales volume. Therefore, drawing inspiration from the research (Lin et al., 2024), market demand, as influenced by both the DPP disclosure level and blockchain, is defined in this research as Eq. (18).

$$D = D_{current} \times (1 + DL \times (1 - B)) \tag{18}$$

$$IA_{retailer} = (DI_{retailer} - I_{retailer})/AT_{retailer} \tag{19}$$

$$DI_{retailer} = DF_{retailer} \times L_{retailer\_proc} \tag{20}$$

$$DF_{retailer} = SMOOTH(D, MA_{retailer}) \tag{21}$$

$$O_{retailer} = MAX(0, IA_{retailer} + DF_{retailer}) \tag{22}$$

When the manufacturer lack access to actual market demand, it can rely solely on the retailer's order information to issue goods. Consequently, the manufacturer's demand forecasts are based on the retailer's orders rather than direct market insights. Additionally, the manufacturer place orders with the component producer and initiate production plans according to these demand forecasts and its own inventory adjustments. These inventory adjustments are influenced by the manufacturer's desired inventory, current inventory, and the time required for inventory adjustment. However, with the information sharing framework integrated by DPPs with blockchain, the manufacturer can receive orders from the retailer, directly observe market demand, and understand the retailer's inventory. Based on this, purchasing, production, and inventory management decisions are finally made. The equations related to the manufacturer activities are outlined in Eqs. (23)–(32).

$$I_{manufacturer}(t) = \int_0^t (PC_{manufacturer}(s) - SR_{manufacturer}(s))ds + I_{manufacturer\_ini} \tag{23}$$

$$SR_{manufacturer} = MIN(RS_{manufacturer}, O_{retailer}) \tag{24}$$

$$PC_{manufacturer} = DELAY1(SR_{component}, L_{manufacturer\_proc}) \tag{25}$$

$$RS_{manufacturer} = IFTHENELSE(I_{manufacturer} \leq 0, 0, I_{manufacturer}/TimeStep) \tag{26}$$

$$O_{manufacturer} = MAX(0, IA_{manufacturer} + DF_{manufacturer}) \tag{27}$$

$$DI_{manufacturer} = DF_{manufacturer} \times L_{manufacturer\_proc} \tag{28}$$

Without the application of the information sharing framework integrated by DPPs with blockchain, the manufacturer's inventory adjustment and demand forecasts are defined in Eqs. (29) and (30).

$$IA_{manufacturer} = (DI_{manufacturer} - I_{manufacturer})/AT_{manufacturer} \tag{29}$$

$$DF_{manufacturer} = SMOOTH(O_{retailer}, MA_{manufacturer}) \tag{30}$$

When the information sharing framework integrated by DPPs with blockchain is applied, the manufacturer's inventory adjustment and demand forecasts are detailed in Eqs. (31) and (32).

$$IA_{manufacturer} = (DI_{manufacturer} \times 2 - I_{manufacturer} - I_{retailer})/AT_{manufacturer} \tag{31}$$

$$DF_{manufacturer} = SMOOTH(D, MA_{manufacturer}) \tag{32}$$

The component producer typically makes forecasts based on the manufacturer's orders. Production plans are initiated based on these demand forecasts and the component producer's inventory adjustments, which are influenced by the component producer's desired inventory, current inventory, and the time required for inventory adjustment. However, with the adoption of the information sharing framework integrated by DPPs with blockchain, the component producer can not only receive orders from the manufacturer but also directly observe market demand and understand the inventory levels of both the manufacturer and the retailer. Consequently, the component producer can make decisions regarding production and inventory management. The equations about the component producer's activities are presented in Eqs. (33)–(42).

$$I_{component}(t) = \int_0^t (PC_{component}(s) + RR_{part}(s) - SR_{component}(s))ds + I_{component\_ini} \tag{33}$$

$$PC_{component} = DELAY1(PR_{component}, L_{component\_prod}) \tag{34}$$

$$SR_{component} = MIN(RS_{component}, O_{manufacturer}) \tag{35}$$

$$RS_{component} = IFTHENELSE(I_{component} \leq 0, 0, I_{component}/TimeStep) \tag{36}$$

$$PR_{component} = MAX(0, IA_{component} + DF_{component}) \tag{37}$$

$$DI_{component} = DF_{component} \times L_{component\_prod} \tag{38}$$

Without the application of the information sharing framework integrated by DPPs with blockchain, the component producer's inventory adjustment and demand forecasting are defined as Eqs. (39) and (40).

$$IA_{component} = (DI_{component} - I_{component})/AT_{component} \quad (39)$$

$$DF_{component} = SMOOTH(O_{manufacturer}, MA_{component}) \quad (40)$$

When the information sharing framework integrated by DPPs with blockchain is applied, the component producer's inventory adjustment and demand forecasting are defined as Eqs. (41) and (42).

$$IA_{component} = (DI_{component} \times 3 - I_{component} - I_{manufacturer} - I_{retailer})/AT_{component} \quad (41)$$

$$DF_{component} = SMOOTH(D, MA_{component}) \quad (42)$$

3.2.4. Model verification

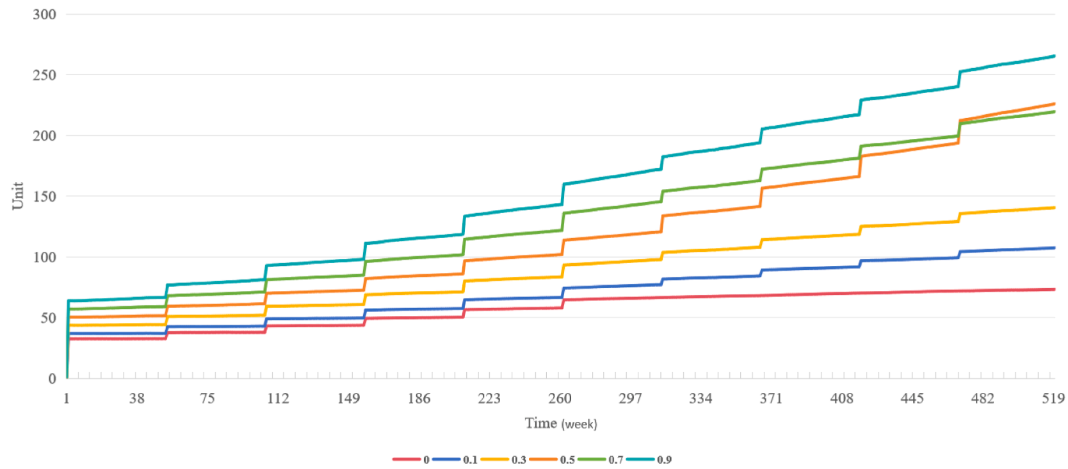
The logic and accuracy of the system dynamic simulation model must be verified (Yang et al., 2023). The proposed model is verified through simulations in Vensim PLE (Version 10.1.4) and through expert evaluations. The main verification processes include assessments of model structure, dimensional consistency, parameters, and extreme conditions. These verifications confirm both the logic and accuracy of the proposed model.

Structure Verification. Model structure verification is conducted to ensure the constructed system dynamics simulation model is coherent and logic. To verify the structure and logic of the proposed model in this research, six experts are invited to participate in interviews to evaluate the appropriateness of the model's logic and structure (Guest et al., 2006). These experts met the following criteria: (1) a minimum educational attainment of a master's degree; (2) over ten years of work experience in supply chain management and logistics operations. Detailed information about the interviewed experts is presented in Table A1. In the interview, each expert is asked, "Does the proposed SFD accurately represent the logical flow and normal operations of a supply chain?" The interview results indicate that all experts confirmed that the model's logic and structure are reasonable and consistent with the principles of

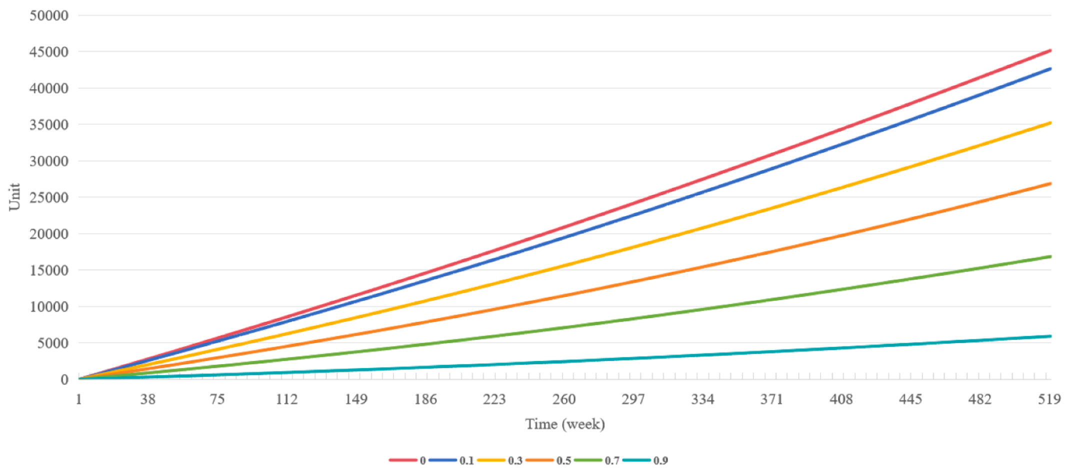
Table 2
Fixed and dynamic parameter setting.

Fixed parameters			
Parameters	**Value**	**Ref.**	
RV_{legal_ini}	0	–	
$RV_{illegal\_ini}$	0	–	
DV_{ini}	0	–	
DR_{normal}	RANDOM UNIFORM (0.9, 0.98)	(CAGDS, 2013)	
$I_{retailer\_ini}$	7000	(CADA, 2023)	
$I_{manufacturer\_ini}$	7000	(CADA, 2023)	
$I_{component\_ini}$	7000	(CADA, 2023)	
DP_{liquid}	60	(CRRA, 2021)	
DP_{solid}	60	(CRRA, 2021)	
PL	780	(CRRA, 2021)	
$T_{inspection}$	RANDOM NORMAL (2,1)	(CAGDS, 2013)	
RD_{part}	RANDOM NORMAL (3,1)	(Wan and Li, 2012)	
RE_{part}	RANDOM NORMAL (0.3,0.1)	(World Auto Steel, 2015)	
$AT_{component}$	5	(Wan and Li, 2012; Yang et al., 2023)	
$AT_{manufacturer}$	3	(Wan and Li, 2012; Yang et al., 2023)	
$AT_{retailer}$	3	(Wan and Li, 2012; Yang et al., 2023)	
$MA_{component}$	3	(Wan and Li, 2012)	
$MA_{manufacturer}$	2	(Wan and Li, 2012)	
$MA_{retailer}$	3	(Wan and Li, 2012)	
$L_{component\_prod}$	RANDOM NORMAL (4,2)	(Yang et al., 2023)	
$L_{manufacturer\_proc}$	RANDOM NORMAL (4,2)	(Yang et al., 2023)	
$L_{retailer\_proc}$	RANDOM NORMAL (2,1)	(Yang et al., 2023)	
Dynamic parameters			
Parameters	***Value***	***Annual growth rate***	***Ref.***
$D_{current}$	RANDOM NORMAL (6769, 2098)	+12 %	(CADA, 2023)
$CR_{illegal}$	0.7	−2.5 %	(CRRA, 2021)
CR_{legal}	0.3	+2.5 %	(CRRA, 2021)
SR	0.016	+0.1 %	(CAGDS, 2013)

*$RV_{illegal\_ini}$: Initial illegal recycling volume; RV_{legal_ini}: Initial collection centre recycling volume; DV_{ini}: Initial disassembly & inspection centre volume; $I_{retailer\_ini}$: Initial retailer inventory; $I_{manufacturer\_ini}$: Initial manufacturer inventory; $I_{component\_ini}$: Initial component producer inventory; DP_{liquid}: Rate of liquid pollutants in illegal dismantling; DP_{solid}: Rate of solid pollutants in illegal dismantling; $CR_{illegal}$: Current illegal recycling rate; CR_{legal}: Current legal recycling rate; DL: DPP disclosure level; B: Blockchain application; PL: Average product lifetime; SR: Scrap rate; $T_{inspection}$: Inspection time; DR_{normal}: Normal dismantling rate; RD_{part}: Recycled parts remanufacturing delay; RE_{part}: Normal recycled parts remanufacturing ratio; $MA_{component}$: Component producer moving average; $MA_{manufacturer}$: Manufacturer moving average; $MA_{retailer}$: Retailer moving average; $D_{current}$: Current market demand; $L_{component\_prod}$: Component producer production lead time; $L_{manufacturer\_proc}$: Manufacturer procurement lead time; $L_{retailer\_proc}$: Retailer procurement lead time; $AT_{component}$: Component producer inventory adjustment time; $AT_{manufacturer}$: Manufacturer inventory adjustment time; $AT_{retailer}$: Retailer inventory adjustment time.



(a)



(b)

Fig. 5. Recycling volumes through legal (a) and illegal (b) channels.

supply chain operations, thereby substantiating the validity of the proposed model.

Dimensional Consistency Verification. The dimensional analysis tool in Vensim software is utilized to verify the model, confirming that the dimensions employed comply with the requirements of system dynamics and actual supply chain operations.

Parameter Verification. Proper parameters setting is essential to ensure that the model functions normally and aligns with real-world supply chain systems. The parameter settings in this research are derived from a combination of previous research findings and data sourced from official statistical agencies, as detailed in Table 2.

Extreme Condition Verification. Ensuring the model's operational success under extreme conditions is vital for maintaining stability. To verify this, market demand is set to zero as an extreme condition, and the resulting inventory levels at various nodes within the supply chain are monitored. The findings demonstrate that all inventory levels remain constant, signifying that inventory fluctuations cease in the absence of product sales, aligning with practical expectations. The extreme testing confirms that the model developed in this research can function effectively under extreme conditions, exhibits a degree of adaptability, and reproduce the true dynamic behavior of the system.

4. Case study

To evaluate the proposed information sharing framework integrating DPPs with blockchain, and to examine its potential impacts on both reverse and forward supply chains, a case study within the automotive industry is conducted using a system dynamics simulation model. The automotive industry is chosen due to its complex, multi-tiered supply chain structure, characterized by multiple stakeholders including component producers, manufacturers, retailers, recyclers, and remanufacturers. These stakeholders face significant information asymmetry, variability in recycling practices, and extensive regulatory oversight. For clarity and practical illustration, this case study explicitly models the lifecycle of end-of-life vehicles, focusing particularly on critical components such as engines. The representative automotive supply chain modeled includes detailed processes such as engine component production, vehicle manufacturing, retail distribution, end-of-life product recycling, dismantling, and remanufacturing. The integration of blockchain and DPPs is illustrated at both the complete vehicle (product-level) and key component levels, emphasizing how lifecycle information from the forward supply chain is utilized to inform reverse logistics operations. Data reflecting typical operational practices in the Chinese automotive industry are utilized to validate the model (summarized in Table 2). To effectively observe the system dynamics, the simulation duration is set to 520 weeks (10 years), with a weekly time step.

4.1. Data collection

Due to practical constraints, comprehensive data for a specific automotive product and component is unavailable. Consequently, the parameters collected and used in this research pertain broadly to typical reverse and forward supply chain processes within China's automotive sector. These parameters, including fixed and dynamic parameters, are sourced from authoritative industry reports, relevant academic literature, and publicly accessible databases, as detailed in Table 2. Dynamic parameters are set based on annual growth rates derived from historical automotive industry data in China. More specifically, the current illegal recycling rate ($CR_{illegal}$) and current legal recycling rate (CR_{legal}) are assumed to decrease and increase annually by 2.5 %, respectively; current market demand ($D_{current}$) grows by 12 % per year; and the scrap rate (SR) increases annually by 0.1 %. Additionally, two critical variables are adjusted to analyze their influence on system dynamics outcomes: blockchain technology application (B), set to 0 when blockchain is utilized and 1 when not; and DPP disclosure level (DL), adjustable within a realistic transparency range of 0.1 to 0.9, acknowledging the inherent industry limitations related to confidentiality of key technologies.

4.2. Results

In this section, the changes before and after the application of the proposed information sharing framework that integrates DPPs

Table 3
Mean and SD value of recycling volumes and accumulated pollutants.

		$RV_{illegal}$	RV_{legal}	P_{liquid}	P_{solid}
Without application ($B = 1$)					
DL = 0	Mean	21592.5	56.6	1295550.5	1295550.5
	SD	13140.6	14.3	788436.5	788436.5
Application ($B = 0$)					
DL = 0.1	Mean	20217.4	70.4	1213046.7	1213046.7
	SD	12401.4	22.9	744083.2	744083.2
DL = 0.3	Mean	16387.6	88.9	983257.1	983257.1
	SD	10246.4	31.3	614786.7	614786.7
DL = 0.5	Mean	12214.2	118.8	732853.9	732853.9
	SD	7801.3	54.1	468077.9	468077.9
DL = 0.7	Mean	7591.4	131.2	455482.9	455482.9
	SD	4908.4	52.1	294505.9	294505.9
DL = 0.9	Mean	2624.8	155.0	157487.4	157487.4
	SD	1722.4	64.4	103344.9	103344.9

with blockchain are analyzed.

The variations in recycling volumes through legal and illegal channels are compared across different DPP disclosure levels (*DL*) of 0, 0.1, 0.3, 0.5, 0.7, and 0.9, as depicted in Fig. 5. Additionally, the mean and standard deviation (SD) values of recycling volumes for end-of-life vehicles through legal and illegal channels, along with the accumulated liquid and solid pollutants in illegal channels, at various DPP disclosure levels are illustrated in Table 3.

The bullwhip effect refers to the amplification of demand information within the supply chain (Lee et al., 1997a). Within the forward supply chain, as information flows from the end customer to the original suppliers, slight variations in demand from downstream enterprises can lead to significant fluctuations in demand information for upstream suppliers (Lee et al., 1997b). This may result in increased inventory costs and disruptions in production planning. The bullwhip effect is quantitatively is defined as Eq. (43) (Disney and Towill, 2006).

$$BullwhipEffect = \sigma^2_{orderingrate}/\sigma^2_{marketdemand} \tag{43}$$

Where $\sigma^2_{orderingrate}$ refers to the variance in the ordering or production rates of enterprises across all levels of the supply chain, and $\sigma^2_{marketdemand}$ indicates the variance in market demand.

Partial changes in the ordering or production rates of enterprises within the forward supply chain are compared across different DPP disclosure levels (*DL*) of 0, 0.1, 0.3, 0.5, 0.7, and 0.9, as depicted in Fig. A1. The values of bullwhip effect for the component producer, the manufacturer, and the retailer are listed in Table 4.

Market fulfillment rate arises from comparing customer expectations with a product's actual performance (Cadotte et al., 1987). Consequently, in this research, market fulfillment rate is quantified by the capacity to fulfill market demand, as specified in Eq. (55). Table 5 details the mean and SD values of market fulfillment rate across different DPP disclosure levels (*DL*) of 0, 0.1, 0.3, 0.5, 0.7, and 0.9.

$$MarketFulfillmentRate = S/D \tag{44}$$

Where S denotes the sales rate, and D is market demand.

5. Discussion

An information sharing framework integrating DPPs with blockchain technology is proposed, which not only encapsulates the core structure of the DPP use case but also presents a reference technical architecture for their integration. Unlike previous studies that have utilized agent-based models (Cammarano et al., 2023), a system dynamics model is applied to evaluate the potential impacts and feasibility of this integrated framework within reverse supply chains, as well as its implications for the forward supply chain. The system dynamics model undergoes verification through assessments of its structure, dimensional consistency, parameters, and extreme conditions. Furthermore, the model is validated using data from China's automotive industry and insights from prior studies, thereby demonstrating the framework's effectiveness and practical viability. The main findings are subsequently discussed.

5.1. Summary of key findings

Initially, the proposed information sharing framework integrates DPPs and blockchain to manage reverse supply chain, serving as a universal reference from cradle-to-gate to gate-to-cradle. This framework involves key stakeholders across the supply chain, as depicted in Fig. 1. Compared to the previous study (Stratmann et al., 2023), the DPP use case framework helps establish foundational standards and clarify the specific information required from each stakeholder, enhancing the management of the reverse supply chain. Furthermore, blockchain supports DPPs by ensuring data immutability, security, and shareability, addressing issues like uncertainty, transparency deficits, and low trust (see Fig. 2) (Lim et al., 2021). This integration can record a complete, unalterable history of value transfers, ensuring product uniqueness and preventing market penetration by counterfeit or refurbished goods. The proposed framework allows for the standardization of processes, promotes DPP adoption supported by blockchain, and sets a base for future system implementation to manage information sharing within the reverse supply chain.

Secondly, applying the proposed information sharing framework integrating the DPPs with blockchain enhances the legal recycling

Table 4
The bullwhip effect values at various DPP disclosure levels.

	$PR_{component}$	$O_{manufacturer}$	$O_{retailer}$	D
Without application ($B = 1$)				
DL* = *0	29.84	18.42	3.29	1.0
Application ($B = 0$)				
DL* = *0.1	14.99	16.98	3.12	1.0
DL* = *0.3	15.02	17.01	3.11	1.0
DL* = *0.5	15.03	17.02	3.10	1.0
DL* = *0.7	15.04	17.02	3.10	1.0
DL* = *0.9	15.05	17.02	3.09	1.0

Table 5
Mean and SD of market fulfillment rate.

	Without application ($B = 1$)	Application ($B = 0$)				
	$DL = 0$	$DL = 0.1$	$DL = 0.3$	$DL = 0.5$	$DL = 0.7$	$DL = 0.9$
Mean	0.9862	0.9879	0.9877	0.9875	0.9873	0.9870
SD	0.0702	0.0604	0.0607	0.0614	0.0622	0.0631

market, thereby reducing the negative environmental impact of illegal recycling activities. More specifically, as DPP disclosure level increases from 0.1 to 0.9, the mean volumes of illegal recycling for end-of-life vehicles notably decrease, while the mean volumes of legal recycling correspondingly increase (see Fig. 5), accompanied by a reduction in both solid and liquid pollutants (see Table 3). These findings aligns with recent literature, which highlights that robust traceability systems, employing technologies such as blockchain, can effectively curb illegal dumping and contamination by ensuring material traceability and accountability throughout recycling processes (Gazeau et al., 2024). Increased transparency limits opportunities for diversion and contamination of recyclable materials, thereby promoting a shift from informal recycling toward regulated, compliant practices. Moreover, digital tracking mechanisms, as facilitated by blockchain-enhanced DPPs, significantly reduce illegal recycling practices such as unauthorized dumping or cross-border illegal trading, as every product and material is verifiably accounted for (Gazeau et al., 2024). Improved accountability and regulatory compliance consequently enhance resource utilization efficiency, mitigate environmental pollution, and facilitate greater oversight and enforcement. These insights directly reflected in the observed reduction in pollutants levels in this research (see Table 3), underscoring the practical value of integrating blockchain with DPPs in promoting sustainability and responsible material management.

Thirdly, the proposed information sharing framework integrating DPPs with blockchain enhances the interaction between demand and inventory information in the forward supply chain, thereby reducing demand variability and mitigating the bullwhip effect. Without applying the proposed framework, the forward supply chain suffers from amplified demand due to limited visibility and fragmented data sharing, leading to heightened information asymmetry and exacerbated bullwhip effects (see Fig. A1(a)). Empirical findings from Wu et al. (2024) indicate that increased supply chain transparency, particularly regarding environmental, social, and governance (ESG) metrics, significantly reduces upstream order fluctuations, with further improvements when transparency is combined with digital tracking technologies, such as DPPs. Similarly, Ponte et al. (2020) highlight that in closed-loop supply chains, enhanced transparency of lead times considerably reduces variability, suggesting that digital lifecycle tracking (e.g., through DPPs) enables manufacturers to better anticipate refurbishment volumes, thus stabilizing production and inventory levels. These findings are consistent with the results of this research: after implementing the proposed framework, comprehensive sharing of market demand and inventory data reduces the bullwhip effect by an average of 5.65 %, 7.65 %, and 49.64 % for the retailer, manufacturer, and component producer, respectively (see Table 4). Notably, the higher reduction observed for component producers reflects the benefit of a more stable supply of remanufactured components, which decreases their sensitivity to market demand fluctuations and supports more predictable production planning.

Fourthly, the application of the proposed framework improves market fulfillment rates and reduces variability, thereby providing a more consistent customer experience. As shown in Table 5, following the application of the proposed framework, the average market fulfillment rate increases by 0.12 %, and the standard deviation decreased by an average of 12.3 %. However, market fulfillment rates slightly decline as DPP disclosure levels rise from 0.1 to 0.9. This counterintuitive trend may be attributed to heightened customer expectations: the enhanced transparency and traceability provided by DPPs can elevate consumer demands for higher-quality products and services, which may not always be fully met, thereby impacting perceived fulfillment rates despite actual improvements in service quality. Further insights from recent studies (Gazeau et al., 2024; Zheng et al., 2022) support this interpretation, suggesting that while verifiable traceability builds trust and generally leads to stable or higher demand, it can simultaneously raise consumer expectations, potentially resulting in a slight decline in fulfillment metrics when those expectations are not entirely satisfied.

5.2. *Theoretical Contribution*

To the best of the authors' knowledge, this research represents the first effort to design an integrated information sharing framework that combines blockchain technology with DPPs for managing reverse supply chains. Addressing identified research gaps (Adisorn et al., 2021; Berger et al., 2023; Nowacki et al., 2023), this research contributes theoretically by explicitly illustrating how DPPs and blockchain can be integrated to mutually offset their respective limitations. Specifically, the proposed framework demonstrates that blockchain not only provides an implementation pathway for DPPs but also significantly enhances information security by offering a tamper-proof, decentralized ledger that ensures data integrity, trustworthiness, and secure stakeholder access. Concurrently, the detailed and standardized data formats of DPPs complement blockchain's functionality by effectively capturing critical product attributes, such as material composition, repair histories, and end-of-life processing instructions, which traditional blockchain implementations alone struggle to manage (Subramanian et al., 2020). This research provides a clear theoretical framework through which the two technologies mutually compensate for each other's limitations. This dual-layer explanation moves beyond a purely technical description and offers a generalizable construct for future work on supply chain information sharing systems.

Furthermore, prior studies on reverse supply chains frequently highlight challenges, such as unclear stakeholder responsibilities and information asymmetry (Bianchini et al., 2019; Xia et al., 2023a; Zhang et al., 2023a). This research extends the theoretical understanding of these issues by showing how integrating DPPs and blockchain comprehensively address such challenges, thus opening new avenues for efficient information management in reverse supply chain processes. The proposed integrated framework clarifies stakeholder responsibilities through immutable data records, mitigates information asymmetry via standardized and transparent product data, and reduces process uncertainties through improved traceability and detailed product lifecycle histories. This extends theoretical understanding of governance in closed-loop supply chains.

In addition, existing literature employing system dynamics to evaluate supply chain behaviors has primarily focused on forward supply chains or aggregate sustainability impacts (Mangla et al., 2021; Roozkhosh et al., 2023). By specifically applying system dynamics modeling to the novel integration of DPP and blockchain in reverse supply chains, this research advances the theoretical understanding of the dynamic complexities arising from integrating these advanced technologies. This research is the first to explore the potential impacts of information sharing enabled by the proposed framework within the reverse supply chain, along with its implications for forward supply chain management, thereby significantly enriching the theoretical discourse on supply chain dynamic information-sharing effects.

5.3. Practical Implication

On a practical level, this research can improve information efficiency throughout the lifecycle of end-of-life products and reduce uncertainties inherent to reverse supply chain processes. Practitioners can leverage this framework to enhance product material traceability and extend material lifespan by maximizing value recovery at product end-of-life stages. The integration of DPPs and blockchain can reduce waste generated by communication barriers, facilitating more effective business collaboration and coordinated decision-making among diverse supply chain stakeholders. This integration can enhance operational performance across both production and reverse logistics activities.

The proposed framework holds potential for broader application across various industries, such as electrical and electronic equipment (EEE), luxury watches, and smartphones. Additionally, the framework provides valuable guidance for policymakers and legislators in shaping industry-specific standards and regulations, supporting improved sustainability practices through clear and enforceable data management requirements.

Finally, the practical insights from this research facilitate the development of stable cross-border trade frameworks and cross-jurisdictional cooperation in closed-loop supply chain management, thereby advancing global circular economy objectives and sustainability goals.

5.4. Limitation

There are certain limitations in this research. First, the impacts of the proposed information sharing framework integrating DPPs with blockchain technology have been evaluated using data from a single supply chain scenario, limiting generalizability. In larger or multi-tiered supply chain networks, significant scalability challenges may arise when adopting blockchain due to technological constraints, such as slower transaction processing speeds and increased computational resource demands as the network expands. Furthermore, potential resistance to DPP adoption among stakeholders may emerge due to concerns about data confidentiality, competitive sensitivity, and the complexity and cost of integration. Such resistance could slow or even undermine the adoption process, limiting the practical effectiveness of the proposed framework. Second, the cost implications associated with constructing and maintaining the proposed framework are not addressed because detailed data are scarce at this early stage of DPP development. This presents another significant limitation, as financial feasibility is a critical factor influencing managerial and stakeholder acceptance. Third, although the model assumes transparency improves demand, it does not empirically examine how different levels of DPP disclosure affect consumers' purchase intentions. Fourth, the current system dynamics model omits potentially important variables such as evolving regulation, changing consumer preferences, and technology learning curves. Fifth, using only a system-dynamics approach may introduce subjectivity when validating stock-and-flow structures.

6. Conclusion

Circular economy is crucial for policymakers, civil society, and academia, particularly in discussions on waste and resource management. A key barrier to transitioning towards a circular economy is the lack of transparency and standardization in data sharing and processes within reverse supply chain. Despite advancements in DPPs and blockchain technologies as solutions to these issues, their isolated applications have been limited in addressing the comprehensive challenges inherent in reverse supply chain management. Moreover, existing literature predominantly examines these technologies independently, with limited empirical evidence demonstrating their integrated effectiveness in practical reverse supply chain contexts.

This research explicitly addresses these gaps by designing a novel information sharing framework that systematically integrates blockchain with DPPs to enhance information management in reverse supply chains. Specifically, blockchain technology not only establishes a secure, immutable, and decentralized data ledger but also mitigates DPP-related information security concerns. Concurrently, the detailed and standardized data structure provided by DPPs complements blockchain's capabilities by effectively capturing comprehensive product lifecycle data that traditional blockchain implementations alone struggle to manage.

Furthermore, this research advances existing knowledge by evaluating the impact of the proposed integrated framework on reverse supply chains using system dynamics modeling. This methodological approach addresses a critical research gap in the literature, wherein few studies have applied system dynamics specifically to the combined implementation of blockchain and DPPs within reverse supply chain contexts. By quantitatively assessing the effects on market fulfillment rates, the bullwhip effect, and environmental impacts, the findings offer robust evidence of how enhanced transparency and standardized product lifecycle data can positively influence both reverse and forward supply chain performance.

Theoretically, this research contributes significantly to existing knowledge by illustrating how the combined application of blockchain and DPPs can address complex supply chain issues in ways that surpass prior approaches. It advances theoretical understanding by demonstrating the integration between blockchain's data security and DPP's detailed data representation capabilities. Practically, the proposed integrated framework offers managers and policymakers a clear pathway toward improved resource recovery efficiency, reduced illegal recycling practices, enhanced supply chain stability, and optimized resource utilization through increased transparency and stakeholder accountability. Ultimately, this research establishes a foundation for enhancing information efficiency in reverse supply chains, thereby aiding in the recovery of end-of-life products and critical resources utilization and supporting the transition to a circular economy.

Future research could explore several concrete directions. First, empirical studies should investigate the proposed integrated framework in multi-tier or cross-sector supply chain contexts (e.g., automotive-electronics networks) to assess its effectiveness and adaptability under more complex conditions. Second, quantitative analyses of the cost-benefit relationships for firms implementing the proposed integration should be conducted, focusing on economic viability, return on investment, and operational impacts. Third, future research could examine consumer behavior in response to varying levels of DPP transparency enabled by blockchain, evaluating how increased information availability influences consumer attitudes and purchasing decisions. Fourth, additional studies should develop more detailed and customized system dynamics models that incorporate variables such as regulatory policies, consumer preferences, and technological maturity to better predict long-term sustainability outcomes and industry-specific implications. Fifth, develop a hybrid model that couples system dynamics with discrete-event simulation (e.g., via AnyLogic) to cross-validate behaviors at both strategic and operational levels, thereby reducing reliance on expert judgement for model adequacy.

CRediT authorship contribution statement

Hanbing Xia: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Jiahong Li:** Writing – original draft. **Qian Jan Li:** Writing – review & editing, Conceptualization. **Jelena Milisavljevic-Syed:** Writing – review & editing, Supervision. **Konstantinos Salonitis:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

For structural validation, a panel of six experts (see Table A1) is consulted. During individual sessions, each expert receives a printed copy of the stock-and-flow diagram together with a concise verbal overview of its principal feedback loops. The experts are then asked a single, uniform face-validity question: "Does the proposed SFD accurately represent the logical flow and normal operations of a supply chain?" They respond on a binary scale ("Yes/No") and are invited to offer additional comments. All six experts answer "Yes," and no structural omissions or logical inconsistencies are identified, thereby confirming the model's adequacy from a practitioner perspective.

Table A1
Detailed information about the interviewed experts.

Expert	Field of profession	Level of education	Years of experience
1	Academia	Ph.D.	21
2		Ph.D.	25
3		Ph.D.	20
4		Ph.D.	12
5	Industry	Master	11
6		Master	12

Table A2
Details of the reference framework for DPP use case across various stakeholders.

Designer	
Technical & design documentation	CAD model; simulation data; design change logs;
Guidelines & procedures	basic assembly & disassembly instructions; maintenance & repair guidelines;
Performance & testing	performance test results; material data sheets;
Environmental information	environmental impact assessment; environmental compliance;
User experience	user experience and feedback;
Design tools and software	design tools & software versions.
Material Supplier	
Identification information	identification number; material batch; producer information;
Chemistry & material composition	material data sheet; safety data sheets; expiry date;
Certification compliance	material certification;
Supplier & storage	supplier information; storage conditions;
Environmental information	environmental footprint; environmental compatibility; disposal & recycling guidelines.
Component Producer	
Guidelines & Procedures	assembly & disassembly instructions; maintenance & repair guidelines;
Identification information	identification number; component batch; producer information;
Production information	production process & conditions; production usage; bills of materials;
Certification compliance	component certification; quality data; test specification; safety data sheets;
Performance & specifications	component data sheet; expiry date;
Environmental information	environmental compatibility; environmental footprint; disposal & recycling guidelines.
Manufacturer	
Guidelines & Procedures	assembly & disassembly instructions; maintenance & repair guidelines;
Identification information	identification number; product batch; manufacturer information;
Production information	manufacturing process & conditions; bills of components;
Certification compliance	product certification; quality data; test specification; safety standards;
Performance & specifications	product data sheet; application specification; expected lifecycle;
Environmental information	environmental footprint; disposal & recycling guidelines.
Distributor	
Customer & market information	customer requirements; sales & distribution records; customer contact information;
Distribution & transportation channels	distribution channel; transportation & logistics records;
Inventory management	storage conditions & handling information; inventory management information.
Maintenance & Repair Provider	
Maintenance & repair record	maintenance date; maintenance service type; repair date; repaired/replaced components; service process;
Fault diagnosis & solutions	fault diagnosis; fault solutions
Service quality	customer feedback & satisfaction to service quality;
Maintenance suggestions	maintenance recommendations & intervals
Environmental information	environmental footprint;
EoL Products Collection Centre	
Product recycling information	recycling location; recycling date; recycled product brand, type, model; final product owner; reason for discard; recycling channels;
Product status & usage history	recycled product status; usage data;
Environmental information	environmental footprint.
Disassembly & Inspection Centre	
Basic disassembly information	disassembly location; disassembly date; disassembly process;
Inspection & valuation	fault & damage assessment; identify recycling mode (remanufactured, reused, refurbished); −current component valuation;
Environmental information	waste & residual material handling; environmental footprint
Safety compliance	safety & compliance information

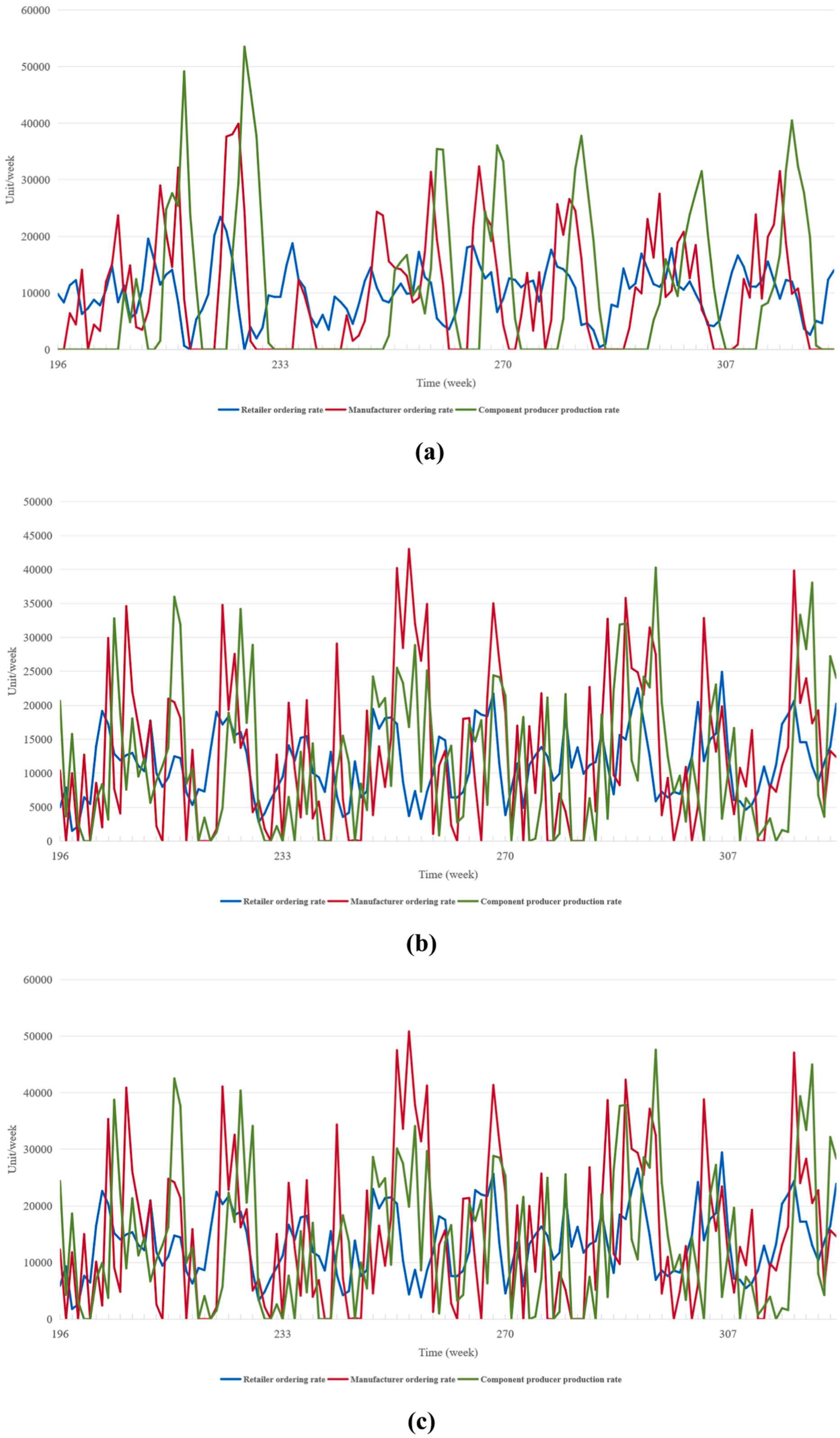
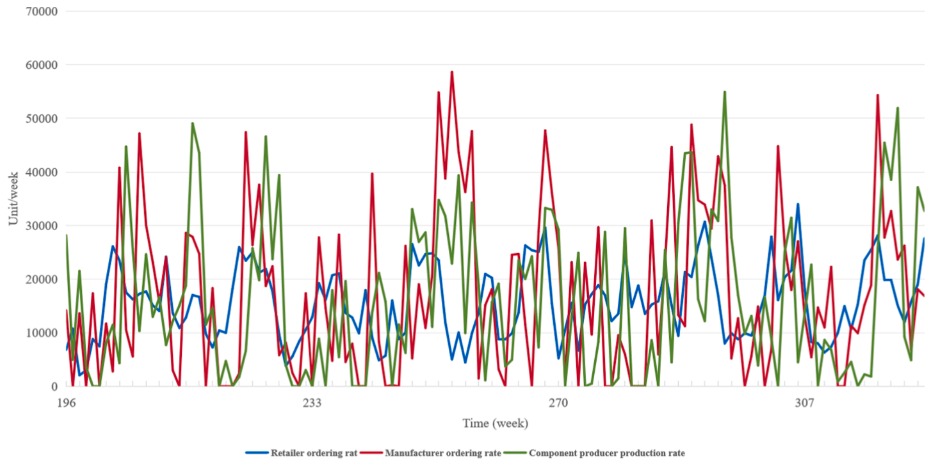
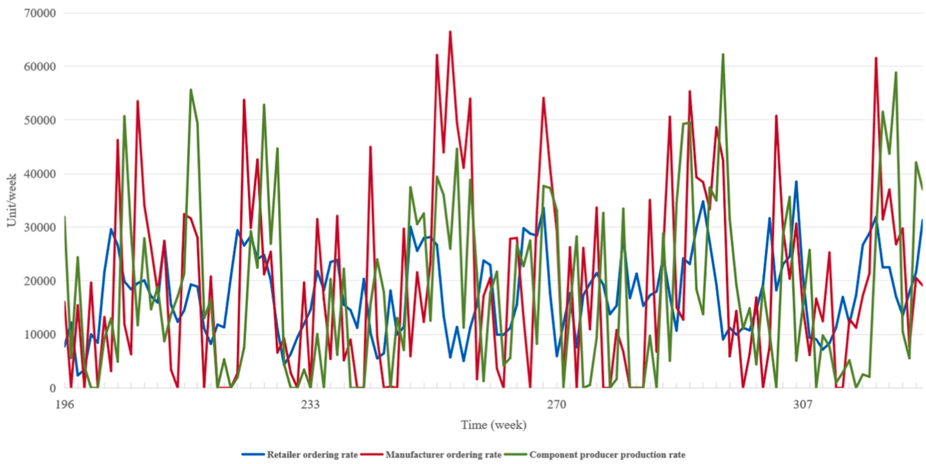

Unit/week
Time (week)
Retailer ordering rate
Manufacturer ordering rate
Component producer production rate
(a)
(b)
(c)

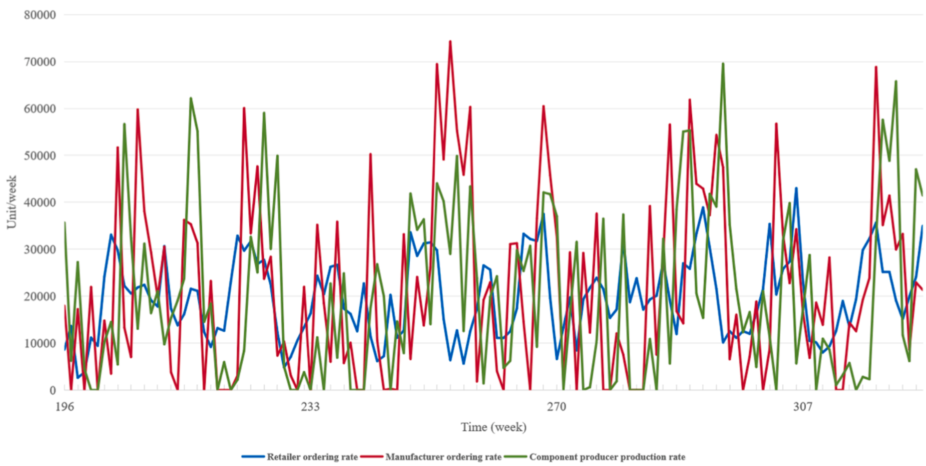
Fig. A1.



(d)



(e)



(f)

Fig. A1. (*continued*).

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