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Digitalizing the Closing-of-the-Loop for Supply Chains: A Transportation and Blockchain Perspective

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Abstract: The circular economy is gaining in importance globally and locally. The COVID-19 crisis, as an exceptional event, showed the limits and the fragility of supply chains, with circular economy practices as a potential solution during and post-COVID. Reverse logistics (RL) is an important dimension of the circular economy which allows management of economic, social, and environmental challenges. Transportation is needed for RL to effectively operate, but research study on this topic has been relatively limited. New digitalization opportunities can enhance transportation and RL, and therefore further enhance the circular economy. This paper proposes to review practical research and concerns at the nexus of transportation, RL, and blockchain as a digitalizing technology. The potential benefits of blockchain technology through example use cases on various aspects of RL and transportation activities are presented. This integration and applications are evaluated using various capability facets of blockchain technology, particularly as an immutable and reliable ledger, a tracking service, a smart contract utility, as marketplace support, and as tokenization and incentivization. We also briefly introduce the physical internet concept within this context. The physical internet paradigm proposed last decade, promises to also disrupt the blockchain, transportation, and RL nexus. We include potential research directions and managerial implications across the blockchain, transportation, and RL nexus.

Keywords: transportation; reverse logistics; blockchain technology; supply chain; sustainability

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1. Introduction

Circular economy transportation is an under investigated yet important issue. The transportation requirements will likely vary depending on the type of material, location, industry, and infrastructure that is available, amongst other factors. For example, building materials, aluminum, steam, oil, and food would each require very different transportation models.

Transportation, including multimodal concerns, network development, and technological issues are all part of the conversation when considering transportation's role in forward and reverse logistics (RL). Investigating these aspects has occurred [1], and many dimensions have been introduced. However, with modern developments of information technology and networked systems—especially blockchain technology—some of the rules for RL and transportation may be rewritten or at least require significantly more investigation. We focus on RL because it is the core activity to closing-the-loop for many circular economy practices.

Given these needs and directions, we provide a review, identifying practical and research concerns, for transportation issues at the nexus of transportation, digitalization, and RL (see Figure 1). We specifically focus on blockchain technology and some linkage to potential synergistic technology such as the Internet of Things (IoT), artificial intelligence, cloud computing, and sensors, that may function within the RL supply chain and support transportation activities and equipment. As an additional dimension we investigate how various elements of the physical internet play a role in this environment.

These advances may be termed Transportation 4.0 within the broader Industry 4.0 conceptualization of emergent operations and industrial technologies. Although there has been a linkage of Industry 4.0 to circular economy practices (e.g., [2]), the nuances of transportation concerns within a closing-the-loop and RL operational context can use further investigation and development—especially within the context of RL which has seen limited emphasis in this environment and require further investigation [3]. In our case the industrial technology we discuss is blockchain technology, one of the most popular and hyped disruptive technologies within the Industry 4.0 conceptualization [4].

Using a popular RL framework of activities—collection, separation and inspection, storage, disassembly, shredding and grinding, and outbound logistics—we identify a series of blockchain–transportation digitalization concerns across various activities and their overall relationship. The transportation concerns include technological, organizational, and economic issues. This general framework sets the stage to understand current practices and future research agendas.

Broadly or locally transportation can play an important role in each RL activity and at multiple levels. When managing a supply chain, security, traceability, transparency, and tokenization can play a role with the emergent digitalization concerns. How these characteristics of the emergent information technologies (digitalization) will be part of the evaluation and categorization. The blockchain dimensions will take a multifaceted and complex set of relationships and topics. We provide both a systemic evaluation that allows for elemental and holistic investigation of these relationships at this nexus.

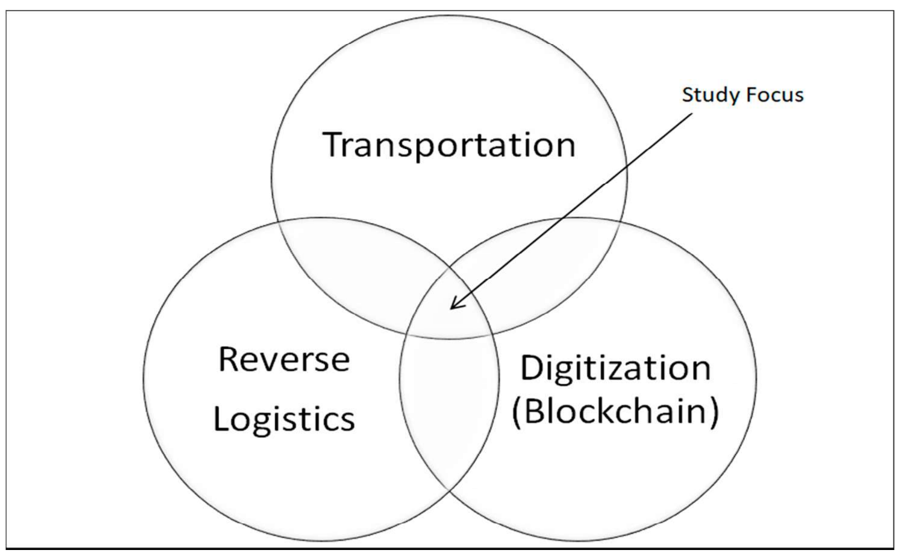

Figure 1. The study focus—examining the nexus of digitalization (blockchain), reverse logistics, and transportation.

The main contributions of this paper are as follows: (1) Discussing, for the first time, the nexus of three topics: Transportation, RL, and blockchain (Figure 1); (2) Highlighting the prevalence and importance of transportation in making RL, and generally, supply chain, efficient, resilient, and sustainable. We also introduce the role of the physical internet paradigm in this nexus. (3) Identifying research and practical opportunities for this nexus.

We introduce these three concepts and make this contribution as a perspective paper. Its main research objective is outlining the main concerns of the nexus of transportation, RL, and blockchain. No study has yet to complete this level of simultaneous evaluation of these three topics based on evidence from practice and research. Some studies may have peripherally and quickly addressed this issue, but usually in just a small section of a much larger review, e.g., [5,6]. Hence, this paper provides a deeper dive into this topic that other studies did not cover. There are some papers that consider blockchain-based systems in transportation (see e.g., [7]) but do not go into additional depth or detail on RL aspects. These aspects can further enhance the circular economy and other organizational closing-the-loop philosophies especially from a transportation perspective. Similarly, there are papers that consider transportation aspects and RL (see e.g., [8]), but neglect blockchain technology and digitalization. Hence, the research aim of the paper is filling a gap in the literature and identifying research streams to fill this obvious gap at the nexus of transportation, RL, and blockchain; all of which are critical for a more sustainable production and consumption ecosystem.

The remainder of this paper delves into some of the issues over the next few sections. The next section provides an overview of RL and blockchain technology with special emphasis on transportation issues within each. Section 3 is devoted to the development of a framework based on blockchain capabilities that integrates blockchain, RL, and transportation. The framework is followed by some examples that provide insights into how the framework may be implemented in the practice. Section 4 balances the potential benefits from Section 3 with limitations and possible enhancements. Exemplary research questions and managerial implications at the nexus of transportation, RL, and blockchain are discussed in Section 5. Finally, Section 6 concludes the paper.

2. Background

In this background we introduce two major subsections related to RL and blockchain technology. We also introduce transportation related issues in each section. These foundational and definitional concerns are first introduced to set the stage for the next section that synthesizes these topics across various blockchain characteristic domains.

2.1. Reverse Logistics Activities and Transportation

Reverse logistics, similar to logistics in the forward supply chain, is likely to have multiple organizations with defined activities. One overview of the activities, flows, and mechanisms (organizations and technologies) involved in the RL chain are shown in Figure 2 [9,10]. The activities include collection, separation and inspection, storage, disassembly processing, shredding and grinding, and outbound logistics. Activities may be owned by the same entity or by different entities. Not all activities are always completed and will depend on the product, components, or materials flowing through the RL channels. For example, plastics RL might require very different structures and activities than RL for railcars or ocean maritime ships. The structures and characteristics of the materials also relate to transportation requirements.

The major activities and mechanisms are each presented. It is these activities and supporting mechanisms that require information management capabilities to help monitor, control, and plan for flows; these elements set the foundation for our latter review of linking blockchain capabilities to reverse logistics. The first major activity is collection which can be proactive or reactive. Proactive collection is when an organization seeks materials for the RL channel and collects them—typically waste management and curbside collection may be in this category or planned remanufacturing of engines. A more reactive approach is to wait for deliveries and returns to occur as centers wait for end-of-life products and materials to be returned.

The type of material flowing into a RL channel may occur for multiple business or regulatory reasons. For example, take-back legislation such as the Waste Electrical and Electronic Equipment (WEEE) regulatory policies [11] are heavily dependent on RL activities from a regulatory product stewardship perspective. These regulations were aimed to help remove hazardous materials from the environment but can also serve an important business function such as capturing high value low-availability resources such as lithium [12].

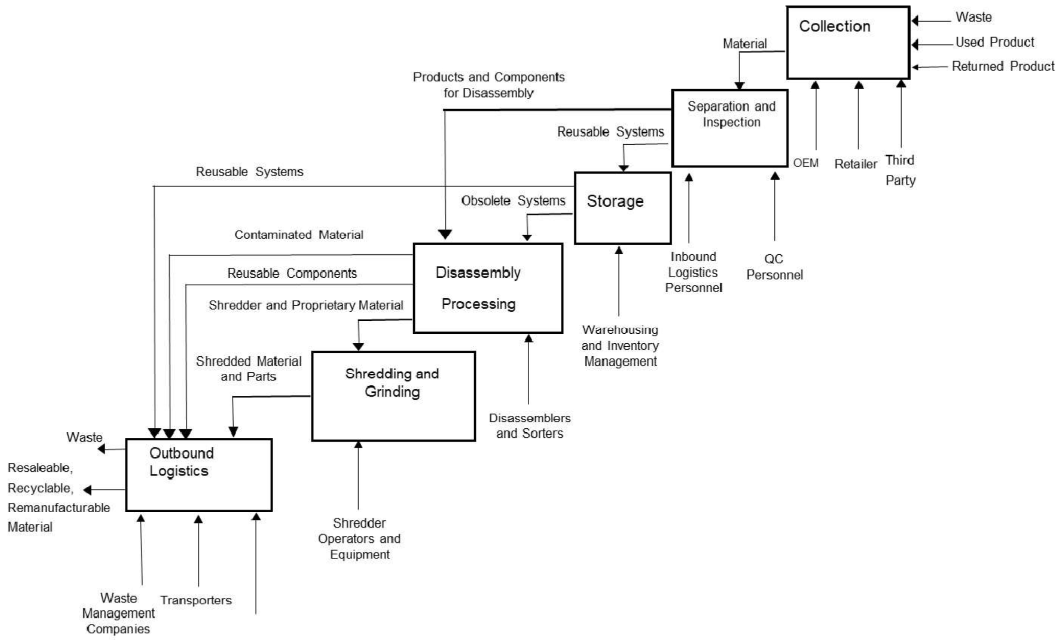

Figure 2. Reverse logistics activities, mechanisms, inputs, and outputs.

Other reasons for collection could include expiring business warranties, leasing, and returns policies. Collection methods may vary depending on the motivation for collection. Mechanisms—from an organizational perspective—include the original equipment manufacturers (OEMS), collection locations and retail locations, and third-party collectors. Various players from the traditional forward supply chain may play roles in the RL collection activities.

The transportation requirements will also vary across these players and approaches; the topic has rarely been investigated as a critical aspect of closing-the-loop research [1,13]. For example, for collection facilities, transportation mode may be determined by individual product and contextual characteristics. If it is a large maritime ship or rail cars, the vehicle itself may be the transportation mode to collect the material. Material and products that are heavy and low cost such as end-of-life building and construction waste materials may need to be transported to collection site by more environmentally efficient vehicles such as barges or trains.

Retail locations that would take back thin plastic film, as an example, would probably rely on foot, cycle, or individual motor vehicle transportation by consumers returning thin film plastics to local retailers and grocers.

After collection from various end-of-life sources, materials need to be transported to separation and inspection locations; alternatively, returned materials may go directly into storage. In some cases, the containers used for shipping, part of an important transportation decision, may require special design and monitoring. For example, international reverse waste streams may actually be shipped in empty shipping containers [14].

Part of the design of a global circular economy may include using maritime shipping containers to ship to other regions of the world for processing later activity stages after collection [15]. Significant business opportunities exist for this network, some estimates include about a $500 billion market using low-cost shipping containers on a "back run"—from West to East or North to South—over global shipping routes [16].

If a global RL network is developed, multimodal approaches and tracking, as centers become larger in the collection, inspection and separation processing. In this case it may require multiple locations to disseminate returned materials to various locations. Few products are a single type of material; thus, after sorting and inspecting materials, components and products, different distribution channels will be used. For some cases the type of material can be solid, liquid, or even gas. Knowing the product and material characteristics coming through the reverse channel may require different types and sizes of shipping alternatives. In many cases multimodal approaches, similar to forward logistics, will be required for RL planning with dependence of design and management even relating to the type of closed-loop activity with remanufacturing requiring different modes than reuse [2].

Storage implies inventory management along RL channels. In this case transportation requirements may relate to warehousing and storage facility characteristics in addition to operational management concerns [17].

The disassembly operations—along with shredding and grinding—although they may be within a single facility location, can also span across multiple facilities and organizations, depending on the product or material. The design of internal systems for movement of material across and within facilities requires transportation planning. One of the difficulties is trying to trace materials as they are further dispersed. Whereas forward logistics focuses on managing disparate incoming flows and locations, RL is more concerned, after disassembly and other decomposition activities, with fanning out distribution of disassembled materials. Although, there may be similarities in delivering multiple products to different locations, in this case the final material or product is further simplified, likely with broader categories for distribution.

The outbound logistics characteristics can be quite varied, as mentioned in various other reverse logistics activities depending on the type of product, material, source, or destination. The distribution on whether something is to be recycled versus remanufacturing or reclamation can each be different. For example, remanufacturing cores—such as engines or frames—may require special carrying and lifting equipment when compared to baled shredded plastics or aluminum. Construction material would require less expensive transportation due to its low value per unit of weight.

Overall, transportation plays a significant role in RL. A number of decisions, design, and management concerns need to be considered to have efficient and environmental friendly RL transportation. Some examples—many more exist—include:

(1) Which mode of transport to use if several alternatives exist? In big cities where there is high pollution (noise, CO_2, etc.), it may be preferable to use small vehicles, bicycles, and even drones if this is in line with legislation.

(2) How can the forward transportation system from a factory to a customer be developed with waste management for RL be managed? Several echelons may be distinguished, transportation from factory to intermediate facility such as a distribution center and from facility to customer. That is, even forward supply distribution may play a role as wastes can be generated at any phase in the process for collection purposes.

(3) How to design backward transportation from a customer to a factory—to pick up a used product and return it back to the factory if the factory or OEM warehouse is the collection site—usually with remanufacturing and warranty-based reverse logistics. Otherwise, there will be additional sites where recycling, reuse, and other activities may occur. There may be many steps, depending on the product, material, or industry, where intermediate facilities for preparation and storage are needed if it is not directly back to the factory. Various and even multi-modal transportation will be needed.

(4) Vehicle characteristics may also come into play. How does design and construction of vehicles vary with the needs of the reverse logistics channel clarified? For example, different compartments for collection/distribution, container types for hazardous versus regular wastes, liquid versus solid would be some examples of different types of materials.

Forward-backward RL transportation decisions, may be made on several levels:

(1) operational level—vehicle routing problem with homogeneous/heterogeneous vehicle; inventory routing problem,
(2) tactical level—expansion of factory capacities, locating facilities including intermediate facilities for distribution/collection/disassemble process; training transportation employees.

(3) strategic level—integrated problem of production planning, facility location, transportation mode, and vehicle determination and acquisition.

Although we do not cover levels of analysis, the decisions can be supported by data at these levels and will require aggregation or disaggregation. Some of these topics will be revisited later as we integrate blockchain technology with transportation and RL issues in a later section. We now introduce some background on blockchain technology.

2.2. Blockchain Technology for Digitalization

Current business and industry landscapes are changing rapidly, requiring flexible, responsive, and efficient closed-loop supply chains to meet recent challenges such as sustainability and resilience. How can organizations and planners to deal with the pressure to cope with ecological and social constraints while delivering profitable business results? A symbiosis between the supply chain and technologies is part of the solution, in particular the integration of blockchain and RL.

Blockchain, popularized by virtual currency, is a digital platform that allows a group of users to create time-stamped, tamper-proof and perpetual records. While its central method consists of securely storing and distributing information, its underlying uses in RL are very promising and therefore exciting. Such technology will allow asset transactions to be shared with greater transparency, substantial accuracy, and without a central control authority while speeding up business processes. Its potential applications and services are extensive, as envisioned by industry experts and technology research firms [18].

The concept of blockchain is so prevalent in the mainstream that many are making it the next major disruptive technology. As a digital revolution, like the Internet, allows the generalization of exchanges throughout the planet without intermediaries. However, according to some research and consulting firms, such as Gartner, the uncertainty remains about its impacts: by 2022, 80% of blockchain supply chain initiatives will remain at a proof-of-concept or pilot stage. The main reason is that early blockchain pursued technology-driven models for supply chains and RL will require different approaches. In this section, we will introduce blockchain technology, present its potential benefits for RL and outline avenues of approaches and models of its adaptation.

2.2.1. The Blockchain

Blockchain is a technology for storing and transmitting information transparently, securely, and operating without a central control body [19]. Blockchains are databases that contain a history of all exchanges between its users since its creation. The database is secure and distributed—it is also known as distributed ledger technology. It is shared by its users without an intermediary, allowing anyone—with permission if it is private—to evaluate the validity of the chain. As its name suggests, it is presented as a series of “blocks” containing data. The blocks are linked together by identifiers, a block contains its own identifier and that of the block before, yielding the “chain” aspect of the blockchain [19].

Blockchain was for many years a technology known only to a few insiders focusing on technical dimensions and characteristics. Over the years, blockchain became popular due to its usefulness for cryptocurrency development—specifically Bitcoin introduced in 2009 by Nakamoto [20]. Bitcoin became a popular investment and financial transaction vehicle—indeed it has become the best performing asset of the last ten years, far ahead of stock market indices such as the S&P 500 or commodities such as oil. A media craze piqued the curiosity of several banking and information technology companies, who sought other uses for blockchain. Today, blockchain is touted as a solution that can improve supply chains and insurance contracts to name a couple popular topics [21,22].

Blockchain has been incorporated into the pantheon of technologies used to support Industry 4.0. Blockchain technology represents an integrative solution to ensure the immutability, security, integrity, and traceability of data across the supply chain. It also plays an important role in the process digitalization as well as improving associated workflow efficiencies.

Some of the major characteristics and capabilities of blockchain are now summarized.

2.2.2. Smart Contracts and Transactions

Smart contracts, as shown in Figure 3, are computer programs, transactional rules, and protocols. These items are intended to automate, facilitate, verify, control, document (legally), or execute relevant actions and events according to a contract, agreement, or approval mechanism. The aim of smart contracts is to reduce the need for intermediaries, arbitration, costs of execution, losses, fraud, malicious, and accidental exceptions or errors [23].

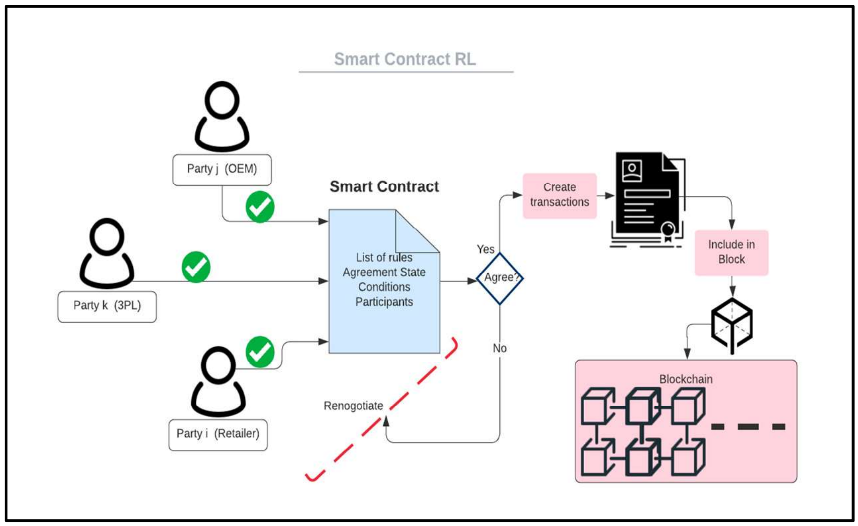

Figure 3. An example smart contract schema.

A transaction is an exchange of assets between partners and managed according to rules. In the context of smart contracts, these rules are typically operationalized through scripting languages (e.g., Bitcoin's Forth) and are used for advanced transactions, such as escrow and multi-party signatures [24]. These rules also form the basis of smart contracts. The past logic is encoded in the form of a script that can be integrated into the blockchain to be run autonomously and to govern transactions. Once a smart contract is integrated into the blockchain, it becomes a tamper-proof and permanent autonomous agent. Regulators use the blockchain to monitor contracts. When executing a transaction or when conditions are met, the controller reads the code, executes it, and processes the results. The smart contract can also be used to codify the terms, rules, stages and conditions of an agreement or a process in a workflow. Ethereum—the second largest cryptocurrency after Bitcoin—is a platform technology that was designed to support smart contracts [24].

Table 1 summarizes some advantages and disadvantages of smart contracts. The main advantages are that smart contracts are immutable, i.e., they cannot be destroyed or contested. The execution does not depend on any subjective interpretation, it is an automation of a set of rules on which participants must agree. The process is faster and more efficient. There is no need to wait for a classical signing procedure—later we discuss the possibility of algorithmic research to improve smart contract processing. The main disadvantages of smart contracts include: risk of hacking them, which could yield modifying their codes and the embedded rules; coding may not be obvious to non-specialist; and the smart contract is not likely to replace legal contracts.

Table 1. Smart contracts advantages and disadvantages.

Advantages	Disadvantages
• A contract recorded electronically in a distributed ledger (DLT) cannot be altered, destroyed or contested. • The execution of the Smart Contract is not linked to interpretations: only the code decides on the total or partial execution of the contract. • Substantially reduce the costs generated by the signing of a contract.	• Risk of hacking: Security flaws in the open-source code could be exploited to modify the terms of the contract, and therefore siphon off funds/info. • Coding may not always be obvious to users: use of a specialist to verify that the code is free from flaws and that it corresponds to the obligations that the parties intend to contract. • The Smart Contract is not intended to replace the legal contract. He remains subject to the law: recourse to legal expertise is always required.

2.2.3. Consensus and Trust

The blockchain environment has been called a "trustless" environment. There is no need for any entity to gate transactions. Within the network, a trust model using group consensus validates transactions and authorizes their addition to the blockchain. Each record in the distributed ledger is verified by the community which holds multiple copies of the blockchain. In the typical information systems transaction validity relies on a central authority. This central authority is assumed to be trusted and is expected to be and remain honest while verifying and clearing transactions. If information is compromised, such as manipulation of hacking, the entire system will experience havoc. The blockchain consensus model avoids these problems by eliminating the central authority and disseminating copies of the records to all parties. The process is potentially more secure than a traditional information management system. With the elimination of trust agents, intermediaries from transactions, blockchain represents a disruptive influence across many industries.

The blockchain builds a trustless system through consensus, as a copy of the records is owned by all parties. In order to ensure integrity a consensus algorithm is required. The consensus algorithm allows the community to ensure that each added block is legitimate and prevents attackers from compromising the chain [25].

The process relies on cryptography mathematics to establish independent trust for each transaction, and on computationally expensive consensus models including: pools of recent transactions are ordered into a block; the block is then cryptographically linked to the blockchain; and, then, verified through a consensus model (mining). Nakamoto suggested using a proof-of-work approach, in which a hard cryptographic puzzle must be solved by miners [20].

There are plenty of approaches for the consensus algorithm, the best known are:

- Proof-of-Work (PoW): The proof of work consensus algorithm is the first consensus algorithm, used by Bitcoin. PoW is performed by so-called miners, people who run the blockchain by providing their computing power, competing to solve a cryptographic problem. These miners help verify each Bitcoin transaction by producing a solution to the cryptographic problem. Over the years, the difficulty of mining Bitcoin has greatly increased, as has the amount of energy used by the network to continue to verify transactions.
- Proof-of-Stake (PoS): This method is used in cryptocurrency. This algorithm assigns a chance to be given the responsibility of validating the next block which is directly proportional to the number of chips involved. For most PoS systems, miners do not receive a reward in new tokens but rather receive the transaction fee. The idea of "wagering" tokens prevents malicious actors from performing fraudulent validations. If actions are falsely validated, the tokens that are put into play are requisitioned. This encourages validators to honestly validate new transactions.

- Delegated Proof-of-Stake (DPoS): The DPoS is similar to PoS in terms of token play, but claims to be a more democratic and fairer system. Instead of probabilistic PoS algorithms, participants in a DPoS network are able to vote. Their vote is based on tokens they put into play by delegates who are responsible for validating transactions on the network. In DPoS, delegates do not need to have a large stake of tokens but compete to win the most votes.
- Proof-of-Authority (PoA): In this approach, only a group of pre-selected authorities, called validators, secure the blockchain and can produce new blocks. New blocks are created when a super-majority is reached by the validators. The identities of all validators are public and verifiable by any third party. Thus, the identity of the validators is the guarantor of their honesty. Since the validators are predetermined, the concern with this algorithm is its preservation from centralization. However, depending on the customer's needs, semi-centralization could be adapted.

2.2.4. Public and Private Blockchains

Blockchains can be classified as public, private or hybrid variants, depending on their application [26]:

- Public blockchains are open to writing (sending and validation of transactions) and reading (free access to the transaction records) without any restriction for access. This does not mean that everything is visible in clear text. Since the blockchain has a high level of encryption, the registry is simply readable by the stakeholders or those who are allowed—those authorized to recognize the transactions.
- Private blockchains—also termed permissioned—has writing or reading reserved for specific users. They use privileges to control the access. Consensus algorithms and mining usually are not required as a single entity has ownership.
- Hybrid blockchains—also termed consortiums—are only available to a privileged group who can read or write the information for the blockchain. The consensus process is controlled using a set of rules agreed to by all members. Copies of the blockchain are only distributed among the consortium.

Figure 4 summarizes the blockchain permission types with various use applications. Public blockchain distributes information in a decentralized peer-to-peer fashion and is used for public and shared issues. Private blockchain has limited access and is used by entities, like enterprises, to record asset transactions within a restricted scope. Hybrid blockchains are similar to small-scale public blockchains. It is decentralized only across a limited participant base, the consortium. The RL process could benefit from all these types depending on the activity considered and the participants.

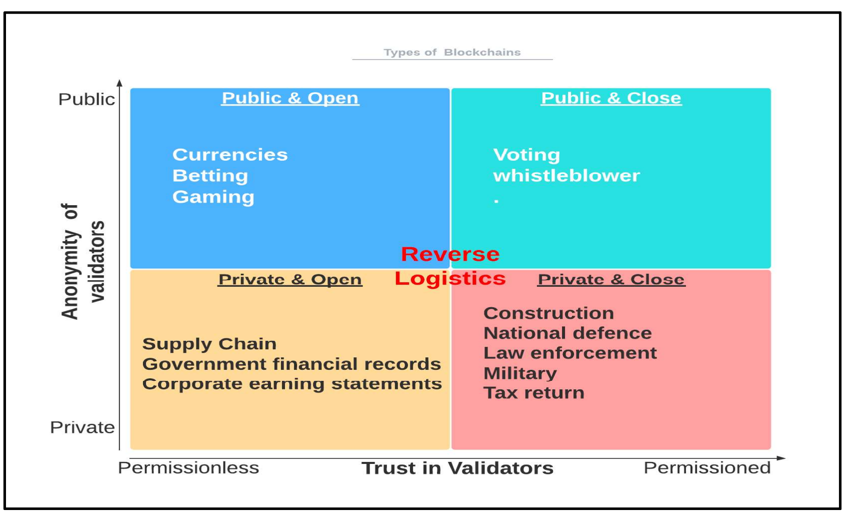

Figure 4. Types of Blockchains and example uses.

2.2.5. Emerging Developments for Enhancing Blockchains

Blockchain has some limitations. A major concern is the slowness of the public blockchain caused by the time needed for the entire network to reach consensus on the state of transactions. This issue causes scalability issues in terms of size and speed of transactions. In the private blockchain there is a need for trust. The integrity of the private blockchain network depends on the credibility of the authorized nodes. To cope with these and other limitations new forms of distributed ledger and blockchain designs are under development. Here, we offer a couple examples which may help address these major concerns:

- The DLT Directed Acyclic Graph (DAG) seeks to improve blockchain performance. The principle of an "oriented acyclic graph" is not new. Indeed, in mathematics (graph theory), a DAG is an oriented graph with no-cycles. An example of a DAG-based blockchain is IOTA's Tangle (https://www.iota.org/, accessed on 24 January 2021). In IOTA, each new transaction must validate at least two transactions that precede it before it can be validated. An algorithm in IOTA ensures that transactions are randomly selected for verification, which prevents network members from validating only their own transactions. This consensus method allows for the simultaneous verification of several transactions. It is simpler and more flexible than the classical blockchain technique consisting in grouping transactions into blocks that can only be validated in a rigid and linear way, one block at a time. Scalability is supposed to be facilitated since the performance of the network is proportional to its use.
- Sharding: Sharding, is Ethereum's solution to scalability. Sharding, or partitioning, is the solution considered by the Ethereum developers to remedy the problem (congestion characterized by longer confirmation times and higher transaction fees). This technique is used for databases: it partitions the data horizontally in order to distribute the storage in memory. For Ethereum sharding would consist of paralleling both the storage and the execution of autonomous contracts without losing security.

In conclusion, the main characteristics of blockchains can be summarized to include four major dimensions that help contribute to overall blockchain capabilities and environment as discussed in the next section:

- Immutability (permanence and inviolability): Blockchain is an immutable and inviolable record of transactions. Once a block is added, it can be neither removed nor modified. This allows trust in the transaction recording and guarantees its sustainability and security.
- Decentralization (network copies): Blockchain is accessible by all members of the network. Stakeholders have access to information and can collaborate in decision making. This facilitates/speeds up the processes which become decentralized.
- Consensus Driven: Each block of the blockchain is verified independently via models and consensus algorithms. The latter rely on mathematics via cryptography to establish independent trust for each transaction and often use a scarce resource (such as computing power) to show proof that an adequate effort has been made. This increases the level of confidence in transactions.
- Transparency (full transaction history): Since the blockchain is an open file, any party can access it and audit transactions. This allows for tracking of assets throughout their entire lifespan.

Together these dimensions offer a variety of opportunities for transportation and RL support. We now discuss various possibilities and use cases that set the stage for future investigation and research.

Given that this paper is a perspective paper, our methodology is based on a thematic review and synthesis of the literature based on the general framework of the three topics and Figure 2—a reverse logistics systems framework. These elements set the stage reviewing the themes in this study. The discussion focused on major concerns based on blockchain linking to Figure 2 with blockchain dimensions described and evaluated in

Section 3. In each of these sections transportation was linked to the other two topics. All three topics with practical and conceptual examples are provided in Section 4.

3. Integration of Blockchain, Reverse Logistics, and Transportation

Blockchain technology goals in supply chain management include ensuring transparency, accuracy, and traceability of data across multiple entities; it can also serve as an incentive tool that can develop new markets and provide efficiencies. Its potential applications due to its information and process management abilities are extensive. The value proposition of blockchains can be summarized across one or more of six elements denoted by the mnemonic ATOMIC (Assets, Trust, Ownership, Money, Identity, and Contracts) [18]. These elements support management and transfer of digital assets through automated validation rules, cryptographically verified rights and ownership, and the validation of transactions without requiring intermediaries—a "trustless" environment. Blockchains can enable new market development with fewer transaction fees and rapid execution. Mougayar [18] also classifies blockchains spanning at least three aspects: blockchain as a development platform with an immutable and reliable ledger; blockchain as a smart contract utility; and blockchain as a marketplace. To these dimensions, we also add two additional blockchain capabilities—blockchain as a tracking service and blockchain for tokenization and incentives. Examples of how each can be used for transportation in a RL environment are presented along these categories, but generic and general examples of how RL and closing-the-loop is supported with blockchain initially begin this section.

3.1. Blockchain Opportunities for Reverse Logistics and Closing-the-Loop

Before linking blockchain opportunities to RL and transportation, we provide some quick examples, with some additional discussion later, of how blockchain digitalization enables RL.

Blockchain technology with its many elements offers opportunities of visibility, through transparency and traceability capabilities, across the supply chain [27] and particularly helps digitalizing the end-of-life supply chain loop closing activities that further support circular economy principles of which RL is critical [28]. Some general RL-blockchain examples include:

- Recording supply chain transactions to ensure information quality, tracking, traceability, and transparency. Data related to RL processes include quantity (of waste, used product or returns), how transfer occurs, the mode of transit, the used assets and resources, and their qualities. Having this information serves additional purposes such as availability of performance metrics and providing customer service.
- Blockchain information can help integrate new technologies, including drones, autonomous vehicles, automated fulfillment centers, open hubs such as the Physical Internet, and cyber–physical technologies. This integration can provide greater benefits together than each alone—that is, there are synergistic benefits. The Internet of Things (IoT), sensors and other technologies can also support this integration of information and technologies [29].
- Public and private blockchains can support sharing information while protecting proprietary and private information. This linkage is critical as some proprietary information may be needed for control, but not necessarily need to be known to competitors and the public.
- Smart contracts can ease transactions by holding actors in the RL channels accountable, maintaining adherence to responsibilities and actions defined within a digital service level agreement; including quality, delivery, and cost performance requirements.
- Integrated with legacy organizational technologies, Blockchain can help reduce the time between process steps, especially for distributed systems, speeding up the ordering, transfer, payment, and ensuring proper, timely movement of products. Accurate, reliable, and secure immutable information will help avoid violations of

international and domestic trade agreements, preventing illicit actions allowing for more ethical international trade of wastes and RL materials.

- Better and optimized circular economy principles, resulting from the ability to provide more visible and reliable information regarding goods, processes, manufacturers, and origin, transfer, and use. This information will lead to better use of resources and help to reach the intention of designing out waste. Products may also be optimized for disassembly and reuse based on gathered information throughout the RL activities.

In summary, potential general applications and use cases include the following:

- holistic and specific RL activities linking transportation to blockchain activities;
- pipeline inventory management through blockchain, with the multiple varieties of disassembled and sorted RL materials;
- decision making from blockchain data and process authentication;
- control inbound and outbound shipments to the RL network with appropriate; identification and management of transport and network resources;
- alleviate the time-consuming tasks of identifying and hiring the right carrier for the appropriate freight, especially given uncertainties;
- reduce costs by eliminating shipping problems to improve effectiveness and efficiency, saving money, and doing more with less;
- in storage facilities to efficiently manage inventory using internal organizational material handling and transportation materials;
- in factories to optimize and plan production for disassembly and remanufacturing using blockchain inventory and quality of component information; and
- in transportation mode selection the ability to link containers, products, materials, and geographical information with transportation mode.

We revisit some of these topics over the next several subsections with broader blockchain characteristics and capabilities, in many cases example literature provides additional detail. We also briefly introduce an additional section we feel is a relatively outstanding area with potential to disrupt this field and the nexus—the concept of the physical internet.

3.2. Blockchain as an Immutable and Reliable Ledger

The requirement to ensure data security and stability is important for managing proprietary information. There are situations when a product or material—at the end-of-life—may contain valuable information in memory chips or hard drives, for example. The knowledge that this information is no longer accessible, and it is confirmed as such, is critical for some organizations who wish to provide their material for recycling or reuse. An example of privacy and managing this from a reliability perspective derives from the reverse logistics and management for cell and smartphones; or even generic plastics that require recycling [30]. Blockchain security and effective permission management including off-chain storage and encrypted transaction, data lessens data access to unauthorized sources and risks. However, immutability can be a negative characteristic if it is managed improperly, especially if proprietary information remains in blocks and cannot be removed [31]. Information from sources and transportation may need to be secured in this situation.

Reliable information will also serve as evidence to authorities that particular products are taken-back in case any organizations (OEMs) are to be questioned in meeting take-back regulations. This monitoring and reliability of information that a product or material is managed effectively at the end-of-life becomes known and may not be changed. This product stewardship information immutability may involve those who transport materials from one source to the other to have specialized keys and permission to be able to alter data and to maintain reliability [32].

Bills of lading used in the transportation service providers industry such as Maersk can be used for tracking materials using blockchain [33]. In this case transporting and exchange of goods along a transportation channel with multiple layers of freight carriers can be made more efficient. Having the appropriate individuals knowing and acting on exchanges of goods during transport can be made more effective and reliable with blockchain technology. An example for access control and data retrieval has been developed for blockchain activities to help maintain control over transactions within RL channels (e.g., see [34]). This can be especially important for international trade of RL materials such as extending the use of computer and cell phone technology by shipping older models to developing countries [35,36]

Certification can be given to organizations who are active in RL operations for greener products. This certification can be evaluated for transportation providers as well—in this case, quality of environmental delivery mechanisms. These certifications may be valuable to differentiate transportation service providers given that third party reverse logistics providers (TPRLP) are predominant sources of RL transport activities. In some cases, legal requirements for disposal and management of end-of-life materials, especially hazardous materials, will require appropriate certification for TPRLP [37].

Knowing certification of transportation mode type and emissions characteristics can help with green management of RL channels. For example, carbon trading across organizations may exist based on emissions from transportation (Scope 1, 2, and 3 emissions) (e.g., see [38]). Hence, having certified modes and emissions through blockchain can make for more accurate carbon emissions trading [39]. This information is very valuable when considering multimodal transportation choices and design for greener and sustainable RL transportation choices.

3.3. Blockchain as a Tracking Service—Transparency and Traceability of Information

Tracking of materials as they flow through various supply chain and RL channels becomes important to identify location and to inform transporters of the necessary resources at various stages. For example, a few dozen lightweight end-of-life cell phones require different resources than having tons of dense building material that needs to be shipped. Knowing quantities, location, type and quality of material will be critical for managing all reverse logistics aspects and especially the type of transportation and storage modes and capacity requirements. Blockchain technology can provide this information broadly and visibly [40].

Traceability is critical for making sure that hazardous material is able to be traced. Its source, and who is accountable will make it more effective for management. Moreover, this information is important for safety and liability concerns [41]. Knowing if there are hazardous materials in RL channels will require that certain carriers and containers are acceptable [6]. Even these carriers and containers may need to be traceable for managing them [42].

Regulations are in place for take-back of end-of-life products and materials. WEEE, for electronics products, requires that electronic materials are taken back at the end-of-life. This may be completed by the OEM, a second party in the supply chain (resellers), or third parties (TPRLP). In each case there may be different transportation requirements and tracing requirements. Backhauling may be used by an OEM, but dedicated transportation equipment would be used by TPRLP. In this latter case blockchain can aid collection of items through crowdshipping—a form of crowdsharing resources—capabilities of forward logistics providers who would like to return with cargo in a reverse logistics situation, especially for materials that can be remanufactured. Example crowdshipping services with reverse logistics possibilities located in India include companies such as FreightBazaar.com, Trucksuvidha.com, and Lorryguru.com [43].

In designing transportation networks, especially with respect to environmental sustainability performance, the use of eco-design—also called design for the environment—for disassembly, reuse, remanufacturing, and recycling is common [44–46]. Eco-design information can be gathered through the blockchain tracking capabilities. Tracking data would include transportation activities and characteristics of transportation vehicles along reverse logistics activities. An example would include design and management of containers based on long term data and vehicle routing when designing products and materials for end-of-life disassembly or collection.

3.4. Blockchain as a Smart Contract Utility

Smart contracts can facilitate, improve or even automate relationships between partners in RL as well as streamline flows. They are able to objectify legal issues, improve the efficiency of business processes, and speed up transactions among other things. For example, managing multiple players and companies, multiple sites and assets, and performing or executing multiple transactions simultaneously, in real time, and under conditions or constraints would be among the activities that are perfectly suited to smart contracts. Indeed, the execution of the smart contract is not linked to interpretations: only the code decides on the total or partial execution of the contract and automatically manages the conditions. In addition, the signatures and validation of a contract are fast, automatic.

In transport problems, and also in RL, a large number of optimization and deep learning algorithms and other artificial intelligence tools are used. These problems cover a wide variety of application and are frequently used to determine the best strategies to help decision-makers in real time, especially in reactive modes (see for example [47–55]). An integration of these algorithms and these tools into the rules included in smart contracts, combined with quality information or data from blockchains will have the advantage of accelerating decision-making and response solutions. These activities can be completed in real time, are automated and autonomous while ensuring the quality of decisions.

In actual situations, data can greatly enhance decision making. Blockchain data may be structured differently, some middle-ware may be useful for systems that link up smart contracts to raw blockchain data. RL data that is not as refined as forward supply chain data may be more effectively controlled and integrated using CRM (customer relationship management), ERP (enterprise resource planning), or MRP (material resource planning) systems [56,57]; this middleware development may allow for transparent linkage of distribution, transportation planning for RL materials with these systems. That is blockchain and smart contracts may help RL and transportation planning (distribution requirements planning) be more effective.

Smart contracts can provide opportunity for improving processes for transportation and reverse logistics. For example, performance measurement for transportation and RL has been viewed to be an important concern [13]. Blockchain, in general, provides ample opportunity to acquire this performance information from many levels of decision making; smart contracts allow for this information and processes to be evaluated and improved over time [58,59]. Having a history of smart contract process details allows for organizations and managers to see how processes have been completed with performance metrics tied to them directly. Such an inter-organizational, longitudinal set of business processes and performance, which has not been well established for transportation and RL, can greatly enhance adoption of these practices.

The physical internet (PI) may be included in RL transportation as well. Every provider in PI should be certified that they have certain capabilities. Assume a RL platform using PI. In this situation a smart contract will allow for a certain provider to carry out RL for hazardous waste PI containership based on whether they meet smart contract requirements or not.

In RL, Gatekeeping refers to the filtering procedures that initiate the return. As not all products should enter the return stream (it depends on issues such as cost, relative value, management, teardown, disposition, SKU proliferation, information, unsafe products, etc.), Gatekeeping identifies how and which products enter this stream. These tasks can be performed in various ways by the retailer or by a returns center under the responsibility of the manufacturer, distributor, or a specialized 3PL. Blockchain and smart contracts, in particular, can help develop the appropriate Gatekeeping. Critical information concerning the identification of the product (serial number, etc.), manufacturer, bill of material, hazardous, involved actor identity, and purchase (invoice, and warranty) could be safely recorded in the appropriate ledger with the relevant access. The rules of return, liability, payment, steps to verify, who is involved could be specified in a smart contract.

3.5. Blockchain as a Marketplace

One way of using blockchain is to use it to build a marketplace or support market efforts. Using blockchain information as a market will depends on material quality, there and purchase and sale of. Organizations may bid on material using blockchain information and smart contracts. Part of this bidding process will relate to transportation by offering transportation as part of cost or bid. Trade can be completed with cryptocurrency based on blockchain technology. This is especially efficient when consideration of international currency exchanges become expensive and cumbersome. This exchange can greatly benefit transportation across national borders allowing for rapid and inexpensive monetary exchange without concern about arbitrage or exchange rates as cryptocurrencies can replace fiat money.

In the category of providing transportation services after sorting and inspection, distributed information on quantities, quality, type of material, and destination possibilities can work well to help transportation providers offer their services and even bid on services through blockchain (e.g., [60]). The blockchain can provide visibility and tracking to the market to determine whether a shipper, through crowdshipping or regular services should bid on taking materials from a sorting location to processing locations such as disassembly or shredding. Smart contracts may serve the role of managing a bidding system (e.g., [61,62]).

Construction and demolition waste (CDW) from construction can become a byproduct that can be traded and recycled [63]. A waste management trading system that treats CDW as a tradeable resource can be completed using blockchain technology. It can also be used to inventory waste for storage and management. Inventorying along the reverse supply chain can be completed for most end-of-life materials using blockchain, while in-transit materials can represent substantial quantities in a transportation network for material such as construction and metals waste.

Crowdshipping was mentioned as a potential blockchain application; one of the limitations of crowdshipping is the lack of trust amongst potential cooperating shipping providers. Blockchain can provide a trusted data and financial exchange method [64].

3.6. Tokenization and Incentivization

The token can be considered a digital twin that depicts products and materials in the form of a token that can trace the materials in a supply chain. This allows stakeholders to follow the newly-defined asset throughout the supply chain; and can be used for payment recording purposes.

Tokenization is a valuable tool to help motivate actions within a supply chain. It can cover multiple aspects of RL. In some instances, tokens can help in collection by offering cryptocurrency credits for returning products such as computers or materials such as plastic film. In this case the transportation infrastructure would include where to place receptacles or collection locations for transportation. Incentivizing through tokenization can provide greater opportunities for collection, ranging from curbside to transportation of materials in bulk from business locations. Tokens can be delivered electronically to anyone in the reverse logistics channel by those who operate the collection or other transportation activities. In this case transportation workers may also serve as purchasing clerks.

Several initiatives on the use of Blockchains and tokens for circularity, the circular economy, and recycling exist [65]. Some practical entrepreneurial examples include RecycleToCoin. This service seeks to increase participation by recycling waste in the UK. Participants are rewarded with virtual tokens when they recycle their plastic and aluminum cans. These tokens are valued as gift cards via GiftPay or given to PlasticBank—a tokenization and incentive mechanism for developing country recycling of ocean plastics [66].

There is a flexibility in the relationship between capital and physical flows in a RL perspective. This flexibility can allow for different transportation designs.

There are many ideas and possibilities that exist. What we have provided are some examples from the literature and from practice. There are many more perspectives, this is only one set that shows how our framework for blockchain, reverse logistics, and transportation can serve as a foundation.

3.7. The Physical Internet, Blockchain, Reverse Logistics, and Transportation

The supply chain suffers from various weaknesses in economic, social, and sustainable aspects. To deal with these challenges a visionary new conception of supply chain management was proposed in the last decade. This new paradigm was inspired from a digital internet network analogy and was termed the physical internet (hereafter PI) [67,68]. There are substantial opportunities for this perspective to be applied to RL as a part of this supply chain with transportation playing a larger and more explicit role. Blockchain, although and information technology solution, can be advantageous to PI efforts.

PI has been introduced at transforming the way physical objects are moved, stored, supplied and used, inspired from the way computers are interconnected through the (digital) Internet. The goal is to reorganize the distribution of goods in an efficient way which is economically, environmentally, and socially sustainable.

Three key elements are needed to ensure the proper functioning of the PI: PI-containers, PI-movers, and PI-nodes. PI-containers are standardized containers. They can be managed and stored by different companies. The PI-movers are used to transport and handle PI-containers such as PI-vehicles (PI-trucks, PI-lifts) and PI-carriers (PI-wagons, and PI-trailers). The PI-nodes are locations for the reception, storage and transfer of PI-containers between PI-movers. PI-nodes can be PI-transits, PI-switches, PI-bridges, or PI-hubs, such as Road-Rail PI-hubs and Road-Road PI-hubs. Note that in each of these PI activities transportation and transportation container aspects play a critical role.

The first aim of the PI paradigm is to make supply chains efficient, effective, and sustainable (see e.g., [69]). For example, there could be a focus on optimizing operations occurring in a Rail–Road PI-Hub cross-docking terminal. Energy consumption is also an example of environmental concern of PI-conveyors used to transfer PI-containers from trains to outbound trucks in a multimodal setting. PI can be compared to the classical cross-dock hubs, as an example of recent sustainability-oriented PI research.

Interestingly there is no detailed and explicit study dedicated to the application of PI in the reverse logistics context—providing a direction of this nexus supported by blockchain.

There are some studies that do initiate this link. For example the Ethereum blockchain and smart contracts can be used to implement a shareable and secured tracking system for hyperconnected logistics, A simulation using the AnyLogic software tool can offer insights on the monitoring of properties depicting shipment lifecycle constraints through a stream of blockchain log events processed by BeepBeep 3, an open source stream processing engine.

There should be a stronger connection between the PI and the blockchain; with RL and transportation playing central roles. Treiblmaier [70] presents a layered framework for logistics that integrates the PI layers with the blockchain. The blockchain affects this architecture, including non-physical layers, non-financial information, and financial information in the form of payments; the reverse logistics connotations require further investigations especially with traceability and tracking of disassembled and sorted goods after inspection. This linkage of collection and disassembly will require newer container capabilities that may be used for disaggregation rather than aggregation, for example. As we have described the PI has many components and elements, relationships with and between PI elements (even automated elements) that can be further enhanced with smart contracts and tokenization to incentivize PI container management.

4. Blockchain Adoption Concerns for Transportation and Reverse Logistics

A number of concerns and barriers exist for study and practice of blockchain, transportation, and RL. Transportation is necessary and well-studied. RL has gained greater importance and study and adoption for the past two to three decades. Thus, most of the difficulties in application and adoption will be related to the limitations and barriers of blockchain technology—the proverbial "new kid on the block".

Currently, academically and practically, blockchain technology is a contested concept [71,72]. The contested concept means that various actors—within the same and different stakeholder groups—have unique definitions, perspectives, with definitions of blockchain capabilities and its elements varying across them. Lack of overall consensus on blockchain—although there is substantial and across-the-board discussion of potential and hype—is a critical barrier to its adoption. Some definitions by investigators are used to support their own agendas, e.g., blockchain developers selling their wares; organizations unable to affect change seeking technology to aid this change; and non-governmental organizations (NGOs) and communities seeking greater transparency may focus one or two aspects of blockchain and consider the technology from that perspective primarily.

Barriers to adoption of blockchain have been categorized in various forms and are a current concern of many studies, which argue for substantial benefits for organizations, but have yet to be broadly adopted (see, for example, [73–76]).

The major blockchain barriers identified—and how they could apply to the specific case of RL and transportation linkages—include general categories such as inter-organizational, intra-organizational, technological, and external or environmental barriers [75,76]. These categories may also fit within the technology–organization–environment (TOE) framework and categorization [77]. Technological concerns have much to do with the immaturity of developments of blockchain technology with scalability as major concern [73]. Organizational concerns relate to a lack of knowledge and management support.

A lack of standards and regulatory concerns are broad external factors that make blockchain technology seem like the "wild-west" of emergent technologies. These limitations are especially pertinent to transportation where cross-board management and a limited governance structure are also very pertinent [58].

Formal analytical modeling such as algorithmic development has become well established in the literature related to transportation and also RL initiatives (e.g., [78,79]) and continues today given the expansion of RL and transportation concerns to a broader circular economy (e.g., [80]). The complexity of these algorithms and models could limit their use within the context of blockchain, RL, and transportation. The challenge may not be for planning purposes, where blockchain data does not have to be real-time but aggregate over a longer time horizon. However, more operational and real-time control, given the scale of data and information requirements may make it currently infeasible for applying these algorithms. Simulation of data based on smaller samples may be used for predictive analytics and inferencing using blockchain data (e.g., [81,82]) if scalability for big data or real-time data is not possible in blockchain technology. Although, as previously mentioned newer developments and algorithms such as sharding improve the promise of blockchain data scalability removing its barrier.

Organizationally, transportation, RL, and blockchain are all very inclined toward multiple partners, stakeholders, and organizations. Having all organizations and decision makers aligned is very difficult, especially at nuanced operational levels. There may be some agreements at strategic levels, but agreement on types of platforms, products and materials to manage, and even mode of transportation becomes a major concern. Sharing of proprietary information may be a major issue from an intellectual property perspective.

External barriers are essentially described within the institutional context and how institutions play a role in governing the nexus. These institutions exist now with governmental regulations and policies for some transportation and RL activities, how they will vary with blockchain requires careful thought given that they may increase adoption barriers instead of limiting the challenge.

The number of concerns and limitations, some of which are presented here, will call into question why policy makers should support these efforts and why companies should adopt them. However, clearly, breaking down some of these barriers will take time and capital resources. Arguing for the benefits and promise may overcome the any stagnation in development. Clearly, these are open for research and managerial investigation, as we discuss in the next section.

5. Discussion

The discussion section will primarily focus on research directions and managerial implications concerning the transportation, RL, and blockchain nexus. Although many streams and issues exist here, we only highlight some promising directions. Given the complexity of the relationships and dimensions the potential on both research and practice is far more extensive than what we initially present; many of the items here are based on previous sections and background.

5.1. Potential Research Directions

The research in this field is relatively fertile. Many gaps in knowledge became evident in almost every example provided within and across the blockchain, transportation, and RL nexus. We highlight some general research topics that are available; this is why we only humbly offer a partial research agenda. A broader research agenda picture includes all variety of methodologies including case studies to understand exemplar best practices, empirical studies to evaluate decision making and adoption theories, and analytical formal modeling development that can help develop optimal prescriptive and engineering solutions for this unique environment.

Blockchain developments have been increasing and improving such as with sharding and tangling—directed acyclic graph algorithms and developments—which allow for scalability to address one of blockchain's most persistent limitations [83]. This characteristic helps to make these applications more feasible, overcoming some of the observed barriers which are likely to be even more serious as the complexity and uncertainties of RL may be greater than these of forward supply chains. Designing blockchain sharding across multiple transportation providers and RL organizations and entities for most effective collection to disassembly to outbound logistics management is necessary.

Smart contracts, as we have seen in potential applications, aid transactions and operations management along the transportation and logistics, including RL, areas. There are also many algorithms that exist for planning and design of such networks (see e.g., [47,49–51,53–55]). Integrating smart contract algorithms with these established RL and transportation models and their effectiveness is an important and valuable area for investigation. From a regulatory-legal perspective the contractual relationships may become more complex and organizations even with similar exchanges may have different transaction decisions depending on the underlying algorithms. Timing of contracts and eventual decisions may become rapid and automated. How this affects overall efficiencies may be simulated and modeled.

From RL and blockchain perspectives, it would be interesting to consider problems where direct transshipment among vehicles is allowed. For example, at a certain location a truck may detach a trailer and another truck may arrive and pick it up [84]. In this case traceability may play a significant role in managing the switching process. In addition, the literature very often considers the combined pick-up and delivery by UAVs (drones) and trucks. For example, a drone is attached to a truck, but at a certain moment it departs from the truck, serves certain clients and comes back again to the same or another truck [85]. This situation is where traceability can play.

It should be noted that drones should be prioritized in the context of RL especially in the case where direct contact among people should be avoided (e.g., as it is the case in the context of COVID-19 outbreak). The use of drones as a transportation device to not only deliver but collect material for RL in an urban setting [86] and blockchain operations for efficiency may need technological evaluation and explicit modeling. This type joint forward and reverse linkage of the same transportation vehicle is part of the crowdshipping and utilization concerns for organizations. Modeling using blockchain information, close to real-time, may become more feasible.

Routing problems may be addressed through some of the flexibilities from blockchain and tokenization. The concerns of collection may be addressed, especially given the uncertainties due to RL sourcing from a variety of sources, with some of these sources representing very small amounts of material such as a single computer or a small bag of recyclables. Understanding and building constraints based on information from the blockchain can greatly enhance activities such as disassembly which require careful evaluation of not only components that flow into the system, but disassembled items that flow out of the RL system.

Synergistic opportunities with other Industry 4.0 technologies exist and require research, development, and adoption investigation. The Internet of Things (IoT) with smart sensors, legacy enterprise technology, cloud computing, and artificial intelligence open numerous possibilities for the supply chain management in general and RL in particular; with transportation as a supporting physical set of activities. The virtual or e-supply chain [56] bears the features such as real-time tracking and monitoring of goods flow in the physical supply chain; and may depend greatly on a blockchain platform for long-term development.

The RL return loop chain is a sensitive supply chain due to specific operations, handling equipment, hazardous materials, pollutions, and varying uncertainties in demand and time cycles. These uncertainties may be due to various returned products, processes, partners, in addition to greater safety and sustainability requirements. This synergistic blockchain-based virtual supply chain can eliminate or change the roles of intermediaries and facilitate transparency, integrity, and authenticity of this complex and sensitive data—data that requires accuracy and certainty—in the RL. Virtualization offers flexible end-to-end services that deploy virtual network functions in the cloud to support the physical network. Blockchain-based solutions will secure operations organization and synchronization in virtualized RL, thus ensuring auditability, transparency, integrity, and efficiency. Whether and how these proposed developments become more prevalent requires multi-disciplinary research from technologists and social scientists, in addition to business and industry studies.

PI can definitely utilize greater investigation in the context of this nexus. The linkage of this topic should begin with whether there is a difference between the physical internet for a typical forward supply chain versus a reverse logistics supply chain. This remains an open question and may have nuances that show some differences, and if these differences exist how they can be remedied by blockchain and related technologies in a transportation setting. For example, a sustainable integrated production-inventory-distribution system through PI has been already studied in the literature [87], but the integration of blockchain policies and reverse logistic process is still an open question.

One of the few studies that has explicitly set the stage for transportation concerns within RL [1] arrived at some major research propositions for investigation. We update these propositions into additional research questions for the transportation, RL, and blockchain nexus. We provide the following adjusted research propositions based on our previous discussions, background and application examples; these adjusted propositions represent potential moderations to the RL and transportation relationship from blockchain technology adoption:

The effectiveness of a transportation system in RL is positively related to the efficient use of existing and proven transportation routes and schedules used for virgin products; this effectiveness is lessened as improved blockchain capabilities are introduced into this relationship; as more routes can be found using blockchain.

The effectiveness of a transportation system in RL is positively related to the use of intermodal transportation on a timely basis; this effectiveness is enhanced due to integrated blockchain elements and capabilities by more rapidly and effectively finding location, capacity, and characteristics.

The effectiveness of a transportation system in RL is positively related to the determination of party responsible for and the estimation of transportation costs for the returned items; this determination and estimation is enhanced by integrated blockchain elements and capabilities.

The effectiveness of a transportation system in RL is positively related to the use of cost-efficient transportation rates (costs); this effectiveness is enhanced due to data availability to better identify rates and routes using blockchain technology elements and capabilities.

The effectiveness of a transportation system in RL is positively related to the availability of detailed shipping and receiving data for the proper handling and management of returned items; this effectiveness is enhanced by more sharing of this data with more accuracy from blockchain and its elements and capabilities.

The effectiveness of a transportation system in RL is positively related to the use of a computer network technology capable of tracking the returned items from inception to disposal; this relationship remains the same since blockchain is capable of doing this, but may be enhanced by having a greater number of parties and transparency.

The effectiveness of a transportation system in RL is positively related to the use of special (colored and marked) bins for distinction between virgin and returned items. The effectiveness may not matter, remain the same, since colored bins may not be necessary if blockchain IoT and sensors are used.

Each of these propositions requires investigation and can be completed using simulations, experiments, case studies and further empirical investigations. Many of these questions for the basic RL and transportation relationship requires investigation. We believe that in most cases, blockchain will have an impact as a moderator of this relationship.

Overall, these are some research directions, many additional examples and specific investigations exist. Each of these broad categories and examples, themselves, offer a series of additional questions for investigation.

5.2. Implications for Management

Blockchain, RL, and Transportation implementation and management will not necessarily be a trivial managerial exercise. Organizations and managers will encounter two relatively recent and unknown practices in blockchain and RL assuming that transportation has been well established for most organizations. If an organization wishes to implement RL and is familiar with forward supply chains, then they will require careful adjustment in their plans and perspectives. If organizations wish to implement blockchain technology, whether in transportation and RL or generally, they will face a multitude of decisions ranging from data to be shared and gathered, to the type of systems and platforms needed within this environment. Given the interorganizational aspects of all these practices, it is usually not up to a single management team or organization on how these three topics will be practically adopted by organizations. We offer a listing of some concerns, but these are only exemplary given the emerging interactions.

Transportation with blockchain technologies and the more complete supply chain in a circular economy (RL) perspective will require investigation by organizations not alone but in partnership with multiple parties including government, suppliers, consumers, universities, and communities [58,88,89]. Forming these partnerships will be critical to adoption and effectiveness of these programs. Working with industrial associations and partners in the supply chain, as well as expert teams in each of these areas will be necessary. Thus, a practical development will require multi-functional teams that have both internal and external partners involved in the best approach for this nexus of topics. Given the potential environmental and social concerns such as safety, the team will likely need to include sustainability and environmental, health, and safety personnel in addition to supply chain, transportation, and information technology personnel.

Legal and regulatory issues will likely arise. Localized regulations may not allow some participation and collaboration amongst these partners. Legal and regulatory issues will likely arise in sharing information but also meeting liability and regulatory constraints [90]. Many take-back and warranty-safety concerns may drive certain characteristics and aspects of RL. Those entities that may offer such services need to clearly understand the context motivating the practices.

Some blockchain and transportation requirements may differ in various locations. For example, if self-driving vehicles will be used for hazardous materials reverse logistics, although safer for human drivers these transportation sources may not be allowed for broader community safety. However, if safe routes are developed through low population density areas they can be utilized. The role of blockchain in this circumstance would be to track materials through the reverse channels as a record of safety.

One of the major dimensions mentioned that blockchain can offer RL and transportation is tokenization and incentives. This element will likely mean financial or monetary exchange. Thus, financial institutions with expertise in these aspects may need to become involved. This element may be limited due to governmental and regulatory rules and concerns [91]. Tokenization and incentivization across organizations and between actors are an emergent field with issues of taxation, corruption, security, and monetary flow. Managers and organizations who wish to use these cryptocurrencies may not be able to do so in some regions; understanding financial exchange laws and guidelines will be necessary for organizations and actors.

The technology will have environmental impact due to digitalization [92]. Additional energy requirements will exist but can the benefits of RL and efficiency in application to environmental issues—such as recycling and resource management—overcome such additional energy usage is a question facing organizations and managers. Relatedly, the concerns for broader greening of supply chains with transportation as a focus may not be separable from the RL decisions, such as backhauling for RL, thus a more holistic planning with the complete greening of supply chains in addition to synergistic technologies (e.g., see [4]) should be carefully considered by managers and planner.

Overall, there are a variety of environmental, economic, technological, and sociological concerns facing management and their supply chains. The barriers and challenges discussed earlier are all concerns facing management. However, the upside potential—which will likely require unique solutions depending on the context—is pretty substantial. Eventually, even with the limitations it is expected that blockchain-type integration for RL and transportation will likely occur and managers within multiple functions and organizations of all types will require knowledge and expertise development [93].

6. Conclusions

The paper evaluates the reverse logistics, transportation, and blockchain nexus. The work provides an overview of existing trends, potential use cases, research gaps, and promising research directions with managerial implications detailed. No previous study simultaneously examined the reverse logistics, transportation, and blockchain nexus. This study addresses a gap in the literature and identifies research streams to bridge this gap. The contribution of this paper is in addressing an important and significant gap in while providing researchers with insights into how to help further understand the nexus. The special emphasis is on RL and transportation since they are core to closing-the-loop for an extensive array of circular economy practices—practices and issues that are driving national and international development policies with strong sustainability goals. The paper elaborates on how transportation aspects should be treated within RL, a relatively under examined and studied issue, by providing some exemplary activities—admittedly some with only the potential use activities—while raising some open research questions. The inclusion of blockchain technology as a digitalization disruptor for RL and transportation will likely require changes in existing policies, practices, norms, and beliefs—for example, trust and its dimensions will require rethinking in this environment.

Blockchain elements and capabilities can leverage some identified dimensions such as an immutable and reliable ledger; blockchain as a tracking service; blockchain as a smart contract utility; blockchain as a marketplace, and blockchain for tokenization and incentives. The discussion is accompanied by corresponding examples of how different blockchain aspects can be used for transportation in a reverse logistics environment.

Although transportation and RL have been studied broadly over the past few decades, blockchain is itself a new paradigm which faces some limitations and barriers. Hence, most future studies need to be devoted to overcoming these issues and efficient implementation of the blockchain within RL and transportation. The research needs to be aligned with recent trends and growing technologies that may enhance the reverse logistics supply chain and support transportation activities and equipment including but not limited to—the physical internet, IoT, artificial intelligence, cloud computing, sensors, drones, and autonomous vehicles. These technologies and practices have the capability to provide transportation and RL synergistic contributions unseen in previous generations—synergies that contribute to a sustainable and better world.

Formal mathematical analytical models and optimization algorithms have seen substantial study over the past few decades, few, if any, consider the blockchain, transportation and RL simultaneously, which may not only contribute to this specific nexus, but a variety of logistics, transportations, and technological nexuses. Blockchain contributes substantial big data opportunities that make existing models inadequate; but study is required. Hence, the future work should be more focused on providing adequate solutions for such cases. Given the exemplary—only very forward-thinking organizations considering their prototyping and adoption—will require best practice case studies to help diffuse knowledge. Broader empirical and even experimental studies can benefit this field.

Overall, although we tried to keep this paper focused and direct, the opportunities that exist are quite extensive. So much so, that not all issues can be addressed in a single paper. Note that no validity technique or methods are presented here, and a specific study on this point is an interesting perspective. We feel that this is really just a continuation of expanding the body of knowledge. The expansion can occur across many more dimensions, disciplines, and thoughts. The world in which we live requires that we carefully consider the complexities so that all benefit including the environment.

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