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Blockchain Practices, Potentials, and Perspectives in Greening Supply Chains

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Abstract: Blockchain technology is an inchoate technology whose current popularity is peaking. Some of the most pervasive blockchain technology use cases exist for supply chains. Sustainable, and especially green, supply chains can benefit from blockchain technology, but there are also caveats. The sustainability and environmental management research and academic literature is only starting to investigate this emergent field. This paper seeks to help advance the discussion and motivate additional practice and research related to green supply chains and blockchain technology. This viewpoint paper provides insight into some of the main dimensions of blockchain technology, an overview of the use cases and issues, and some general research areas for further investigation.

Keywords: blockchain; supply chain; green supply chain; use cases; applications

1. Introduction

Technological advancements have caused a revisiting of sustainability practices. According to ecological modernization theory, technology can help decouple environmental degradation from economic growth [1]. In some cases, technology can benefit both dimensions. As the triple-bottom-line sustainability definition includes social dimensions, whether technology can contribute to all dimensions of sustainability is unclear.

Advances in technology are broad-based and include a variety of production, information, and social technologies. These technologies include current and future developments in such disparate, but possibly interrelated, areas such as additive manufacturing, micro-factories, nanotechnology, Internet of Things (IoT), self-driving vehicles, sharing economies, and blockchain technology [2]. Each of these technologies has implications for the sustainability of organizations and especially their supply chains.

Supply chain management is critical for managing sustainability at global and local levels. Whether the focus is on environmental and green initiatives or social responsibility, the largest and deepest influences are supply chain activities. Of all technological developments, blockchain technology can have profound implications for supply chain sustainability, also known as distributed ledger technology. Although we devote a whole section to the definition of blockchain technology and general characteristics, we define it as decentralized databases or ledgers of records that are shared among networks and supply chain participants. In blockchains, records and data are secure, traceable, and auditable, and maintained on a peer-to-peer network [3]. The contribution of this paper is providing insights into the potential application of this nascent technology to facilitate green practices in supply chains. Our discussion is grounded on the current understanding of blockchain technology and green supply chain management literature. The evaluation framework used in this study was proposed by Hervani et al. [4]. This study would help managers, researchers, and practitioners to further evaluate the potential usage of blockchain technology to improve sustainability, especially along the supply chain.

To further clarify, we provide some insights into the various sustainability-oriented opportunities associated with blockchain technology use cases that occur across and within the supply chain. The supply chain activities include those occurring in upstream, internal organizational, downstream, and loop-closing functions [4]. There are similar relationships and implications for each of these activity groups, and there are also unique activity specific cases. After examples are provided, some general research questions are posited. We think this discussion furthers the need to carefully study how blockchain technology specifically, and disruptive technology in general, require more nuanced investigation in sustainable supply chain practice and research.

2. Blockchain Technology

Blockchain technology became popular through the advancement of cryptocurrency and bitcoin after the 2008 financial crisis [5]. Although the primary focus had been on financial applications, the unique characteristics of blockchain technology inspired broader use of this technology in different markets and even for non-financial business purposes. Supply chains [6], real estate [7,8], government [9], healthcare [10], and energy sector [11] use cases have been some effective applications.

Blockchain technology has a number of general characteristics. The integration of these characteristics differentiate blockchain from other similar information technologies. Unlike other business information technologies, blockchain technology uses a unique data structure that stores data as a chain of blocks. Once a new transaction is recorded on the system, it builds a block that is linked to the previous blocks, creating a chain [5].

In terms of openness and access to data, two popular types of blockchain exist: public and private. In the public blockchain, which is generally permissionless, ledgers are publicly available and anyone can record transactions and track the historical transaction on the ledgers. Popular cryptocurrencies, such as bitcoin and ether from Ethereum, were developed on public blockchains. Public blockchains require a high level of security and reliability due to the existence of anonymous users and the lack of trust among them [12].

In a private blockchain, users are known and ledgers are shared among a private group of participants. In a private or permissioned blockchain, access is restricted to a defined group of participants. A validator allows participants to join the system, provides permission to the ledgers, and maintains the privacy needs of the network [9,13]. Depending on the type of blockchain, the characteristics slightly change.

Although the main features of both blockchains may overlap and vary in some of the literature, we discuss some of the more popular characteristics. Included amongst these characteristics are decentralized databases, data security, information transparency, information immutability, and smart contracts.

2.1. Decentralized Database

Decentralization is an essential characteristic of blockchain technology. In blockchains, no central database, organization, or authority is typically involved in transactions. Decentralized databases of records allow participants in the network to directly interact via a peer-to-peer network. Every participant in the network has the same copy of the ledgers, which are updated with new information or changes in the recorded information in a decentralized manner [3].

Every update in a ledger requires consensus among the network partners. Decentralized consensus is the core of blockchain, which utilizes various algorithms such as proof of work and proof of stake to confirm the reliability of a recorded transaction. Generally, decentralized consensus includes votes or validation of the majority of participants of a network for ensuring the credibility of transactions. Public blockchains require heavy use of consensus algorithms that consume a great amount of power and energy. This characteristic contributes to environmental degradation and negatively affects sustainability values [14].

In a private or permissioned blockchain, the consensus requirement is a set of rules that is defined by the network participants for adding and updating transactions to ledgers. Consensus rules in a private network provide flexibility and ease the use of cumbersome consensus algorithms.

2.2. Security

Information is maintained as blocks within blockchain technology. Each block has a timestamp and a hash value that refers to previous blocks on the chain. Hash values have unique cryptographic structures that prevent tampering and altering the information in the blockchain [15]. Cryptography logic facilitates authentication and trading for anonymous parties, which is a necessity in public, permissionless blockchains, improving the trust and security of the system.

In a private/permissioned blockchain, the trust in the validator, who gives permission to the parties to record and trace information, plays an important role [16]. Security is improved by the decentralized structure of the blockchain. As a result of decentralization, the validity of information is examined by network members based on the consensus rules. This characteristic confines the data misuse and network manipulation. Decentralization also ensures the network is less vulnerable to hacking or crashing. The single point of failure is a common security problem of centralized databases, which has been alleviated by the use of blockchain technology [9].

The timestamp plays a critical role in the supply chain given various time-based competitive issues, such as lead time, delivery, and perishability concerns. The timestamp is also critical to traceability and information transparency.

2.3. Information Transparency

Authorized blockchain network participants maintain the same copy of a ledger, which contains a list of transactions. The ledgers are updated with the most recent approved transactions. A complete history of transactions are visible to the network members, allowing for auditability and traceability [17]. The level of transparency provided by the blockchain enhances fairness and ease of access to data within a network [3]. Transparent information removes intermediaries involved in the processes, increases efficiency, and reduces risks [15].

Growing customer demands for supply chain transparency motivate the application of blockchain technology for supply chain processes. A high degree of transparency provides fundamentals for tracking the origin and flow of products and processes, the parties involved in transactions, and transportation information. Supply chain partners from upstream to end customers can follow and audit the history of records. Since records on the blockchain are time-stamped and secure, data manipulation and fraud are detectable and traceable on the ledgers. This provides trust and reliability for supply chain partners [18]. Tracking technologies, such as radio frequency identification (RFID), the IoT, and smart devices link the physical product to the respective electronic records, creating inputs for blockchain technology that are maintained on transparent ledgers [19].

2.4. Data and Information Immutability

Blockchain data and information are immutable. Immutability means that records cannot be changed or modified without network member consensus. Participants can be confident that the history of records are reliable and unaltered. Theoretically, this feature comes from the append-only concept of the blockchain, which means records can only be added to ledgers and cannot be modified or removed. However, on a public or permissionless blockchain, where miners vote for transactions and control the system, collusion is possible if the majority of miners decide to alter or remove a transaction. Alternatively, change and removing information on a private or permissioned blockchain requires notifying the network members and follows certain agreements and approval requirements [9,16].

2.5. Smart Contracts

Smart contracts are computer codes and scripts that contain terms of contracts and business rules. Smart contracts automatically execute the terms of agreements. Smart contracts check the pre-determined conditions including rules and penalties that are agreed to by parties and trigger the related action to those conditions.

The conditions and terms of contracts are validated by network members [20]. These computer codes are self-executives seeking to eliminate human intervention in contracts. Unlike traditional contracts where trust between parties plays an important role, smart contracts remove the need for trust. Terms of contracts and the related legal actions are digitally written as computer programs and stored on the blockchain platform. The digital contracts remove human judgement from transactions. The role of intermediaries, such as financial professionals and legal people that are involved in traditional contracts, can be minimized through smart contract use. The resulting disintermediation improves efficiency and reduces the costs of business activities.

An example of smart contracts is an automatic payment that is performed when a certain regulation is met or a particular value is added to a product [3,21]. Transactions need to be verified to be added to the ledgers in blockchain technology. The process of transaction validation by network participants can be facilitated through smart contracts. The validation requirements and consensus rules can be regulated by network members and maintained as digital contracts. Smart contracts can check the pre-defined conditions for approving transactions and add them to the ledgers. Similarly, a change in the approved transactions can follow particular regulations that are stored on smart contracts. This digital transaction approval can simplify the use of blockchain technology in complex and private business networks.

3. Green and Sustainable Supply Chains: Blockchain Use Cases and Potentialities

The supply chain has numerous intra- and inter-organizational activities. Figure 1 provides a supply chain activities diagram that incorporates a closed loop perspective with some environmental sustainability dimensions [4]. The activities generally include: (1) upstream vendor/supplier management concerns, such as supplier selection and development; (2) upstream purchasing, inbound logistics, and inventory management activities; (3) internal operations and productions activities; (4) downstream activities including distribution, green marketing, and consumerism; and (5) closing-the-loop activities such as reverse logistics and the various "Re's", such as recycle, reuse, remanufacture and reclaim. Additional activities and resources needed for the supply chain included in Figure 1 are aspects of waste management, energy utilization, and design concerns.

Based on our observations of a wide range of industries and arguments advanced by practitioners and the more popular business literature, we compiled a number of practical business use cases for greening supply chains. These supply chain activities and exemplary blockchain use cases and possibilities are detailed below. A summary of these use cases and possibilities appears in Figure 1 in the dashed circles.

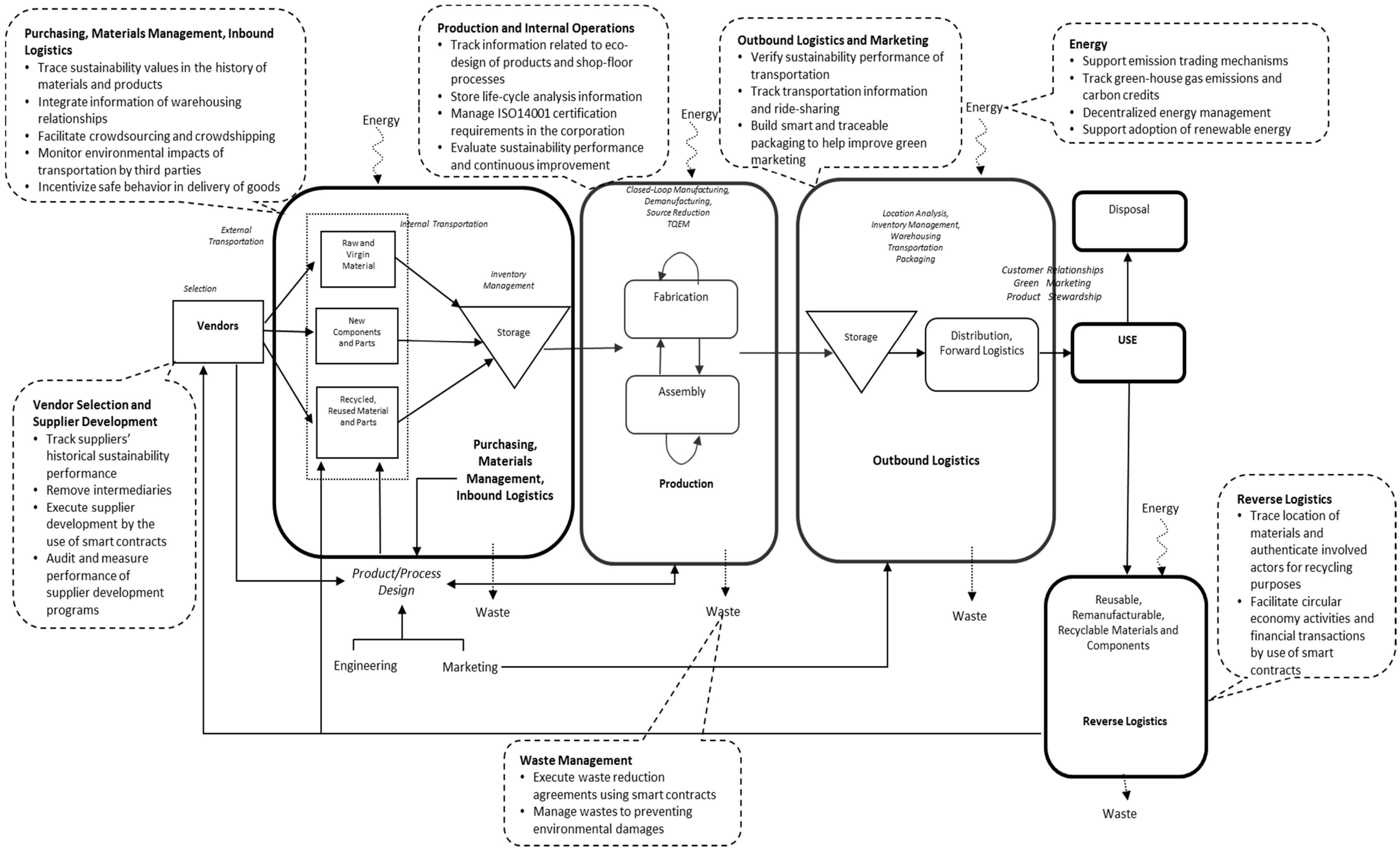

Figure 1. Blockchain application in green supply chain activities.

3.1. Vendor Selection

Supplier and vendor selection is viewed by industry and academia as a critical issue for the long-term success of supply chains. Careful selection and evaluation of suppliers are necessary initial steps to ensure the sustainability of supply chains [22]. It is this upstream portion of the supply chain that has the most profound influence on overall supply chain sustainability. Issues in the upstream supply chain can be easily hidden from buying organizations, furthering their exposure to risk and affecting supply chain resilience [23].

Supplier selection and evaluation in a sustainability context is a multi-dimensional and complex problem [24]. Usually, supplier selection and evaluation is dependent on information. This information is not easily accessible, certifiable, and audited, especially in non-economic, social and environmental, sustainability dimensions [25]. It is this major sustainable information limitation barrier that can be effectively alleviated using blockchain technology.

Vendor historical performance and sustainability data can be made available on the blockchain. This accurate and secure data about vendors' environmental performance help companies to improve their vendor selection processes based on green performance values. Using blockchain not only facilitates the vendor selection processes, but provides information regarding the whole supply chain across multiple tiers and sub-suppliers [26]. The shared information on the blockchain provides companies the opportunity to help their suppliers in selecting their vendors in different tiers of the supply chain. This would help reduce the risk for the focal companies. Removing intermediaries is also an important outcome that enhances the vendor selection process in the supply chain and reduces costs.

Current supply chain sustainability database systems exist such as the Business Social Compliance Initiative (BSCI) database for voluntary supplier social and environmental auditing in the textile supply chain [27]. These databases are available, in some form, to BSCI participants. One of the limitations of BSCI, as with other voluntary databases, is the validity and credibility of their data and audits. Blockchain technology and processes can help address some of these credibility and validity concerns and potentially satisfy third-party and non-governmental organizations (NGOs). These databases may be used for supplier monitoring, development, and selection; their credibility and accessibility can only further support these initiatives.

3.2. Supplier Development

Blockchain technology can help improve supplier development programs. The amount of investment in a supplier development program can be recorded on the blockchain platform. The type of knowledge that is exchanged and the type of organizational support has been given to the suppliers are traceable through the smart contract. The recorded information provides the basis for performance measurement of supplier development programs. Comparison between the performance before and after implementing a training program is possible on the blockchain. By means of smart contract, companies can ensure that they trade with suppliers that are involved in supplier development programs. This can also be a principle for selecting suppliers.

Environmental performance measurement and benchmarking systems will be valuable in determining potentially problematic suppliers within the supply chain. There will be issues of direct green supplier and sub-supplier development concerns. It is these traditionally invisible entities in the supply chain that can be the most environmentally risky and poorly performing members of the supply chain. Visibility further down the supply chain can more effectively identify potential sub-suppliers that may require green development and support [26].

Organizations such as Dell, IBM, Lucent, and Pepsico have extensive environmental supplier development and training programs [28]. These organizations need to record and monitor suppliers included in their programs, which can number in the thousands of suppliers. Documenting and monitoring these suppliers also allows them to build their supplier capabilities and share them with a broader set of customers. That is, not only will the direct suppliers such as Dell, IBM and Lucent have knowledge of their green development, but other customers can potentially have access through industry associations such as the Electronic Industry Citizenship Coalition (EICC).

3.3. Purchasing

Instead of supplier data, product and material data and movement can be maintained on the blockchain. Every product can have several transactional characteristics that are recorded on the blockchain, along with the historical data of a product. These transactions may declare the origin of the product, the quality, quantity, owners, and time. These data provide the ability to trace green quality, recyclability, and carbon footprints. The environmental information ensures customers are aware of safe and sustainable production and transportation of goods. Therefore, customers, with the ability to access this information, would have the opportunity to select sustainable products [29].

To ensure sustainable purchasing, companies can track the journey of resources for rare and high value products. The ability to track the source of products to address biodiversity concerns and contribution of products to resource depletion are two cases that demonstrate the role of blockchains in ensuring the sustainability of products. Using blockchain technology, life-cycle analysis of products can be completed using actual product data, rather than by estimating the values, such as in current life cycle analysis methods, as demonstrated by Favi et al. [30]. This accurate and actual information is a revolutionary contribution of blockchain technology in the life-cycle analysis domain.

3.4. Materials Management and Inbound Logistics

The location and type of facilities, and design of logistics networks to ensure sustainability can be supported with blockchain data. One particular issue is inventory management in a supply chain through warehousing. A significant amount of warehousing is outsourced to third-party logistics providers. Currently, disparate information systems are used to manage these warehousing relationships. Reduction of auditing and compliance for 'bonded warehouses', as well as tracing products and materials can all be supported through blockchains. Cross-border trade will be influenced from a tracking, finance, and scheduling perspective.

In these cases, traceability and auditing increase the sustainability of the warehouse operations by lessening waste due to product and materials loss. Also, scheduling and planning can be more effective by having utilization information for a network of warehousing choices. Alternatively, the increased use of blockchain in these settings, as in all settings, requires additional energy usage.

Another emergent warehousing and logistics issue is crowdsourcing. Crowdsourcing is an outsourcing strategy that places an open invitation to a broad group of participants to perform a task. This approach is similar to the sharing economy situation someone who has available capacity for storage or delivery can respond to these requests. FLEXE is a company that allows anyone with temporary warehouse capacity to sell it to those that need the space. Companies such as Rideship, Zipmets, and Deliv all provide services for crowdshipping. This crowdshipping takes advantage of nearby delivery services with the ability to service local needs. It also reduces the need to build additional warehousing and vehicles, and increases efficiencies associated with consolidation of materials. All these are win-win, joint environmental and economic benefits, providing opportunities for logistics providers.

A difficulty of these current sharing systems are transaction costs, with most of the benefits accrued by the service providers. The more democratic blockchain systems allow for a broader set of participants, potentially aiding, from a social sustainability perspective, lower income regions and individuals. There are current concerns with the use of blockchain crowdsourcing-related malicious agents in all areas of blockchain processing and activities (see [31]). In addition, there are more secured payment possibilities through the use of cryptocurrencies and tokens, which are pervasive due to blockchain technology.

Transportation between and among facilities is central to both outbound and inbound logistics. When contracting with a third-party transportation company, tracing and monitoring transportation will benefit from blockchain technology [29,32]. Transportation causes significant environmental damage and is one of the highest emitters of greenhouse gas emissions, local air pollutants causing smog, and contributes to depletion of energy resources. On the in-bound side, tracing the performance of transport vehicles, as with truckers for example, uses electronic logging devices. Fraudulent actions can occur in the truckers' logs that owners may ignore for purposes of expediency. Some of these behaviors may cause environmental damage, such as driving faster increases emissions and fuel usage.

Changing driver behavior is an important way to save energy resources and improve safe driving. Utilizing cryptocurrency tokens could effectively reward drivers for safe and green practices; these practices may be monitored using blockchain technology with mobile technology. Most current incentive systems are tasked with delivering products quickly and only being rewarded when driving certain distances. These current incentives cause dangerous and unsustainable practices, such as drivers speeding more often and driving longer than allocated hours, creating dangerous conditions.

Building trust in the technology, its broad adoption, and agreed upon industry standards are all issues facing the adoption of blockchain in transportation.

3.5. Production and Internal Operations

Production and operations are internal activities within an organization. Whether the production is based on manufacturing goods or delivering services, the transformation of inputs into outputs are central activities of the production stage. Traditional goods manufacturing includes fabricating or assembly activities. Internal production and supply chain activities require environmental management practices, including production management, environmental management systems, eco-design, performance measurement, environmental accounting, reporting, life cycle analysis, source reduction, closed loop internal systems, and a variety of similar greening practices, that fall within the purview of the focal organization.

A linkage of these green practices to external blockchain activities resulting from upstream, downstream, and closed-loop activities needs investigation and determination. Each of the practices and systems can be profoundly influenced from resources and inventory management, flow of materials across the shop floor, to eco-design of products.

The ISO 14001 standards are a popular global environmental management system (EMS) certification. EMSs are critical to internal operations environmental management. Blockchain implications relate to acquiring and maintaining certification. The use of audit teams to certify ISO 14001 organizations may be influenced by the technology. ISO 14001 is dependent on documentation for full certification. This documentation is then audited. Additionally, ISO 14001 certification can occur simultaneously for all sites of a corporation. For multinational corporations that are distributed broadly, distributed ledger and blockchain systems can prove a valuable resource for accumulating, aggregating, and certifying dispersed documentation. Auditing for initial or recertification may become more efficient, and may even not be needed, as documentation can be evaluated and updated continuously.

Within environmental management systems, there are numerous sub-systems, especially with respect to ISO 14000 certification family modules. These subsystem standards include performance measurements, life cycle analysis, climate change, eco-design, and communications. Monitoring environmental performance measurements throughout an organization and its supply chain through a distributed verifiable system provides more accurate data for environmental management purposes. Central to EMS and production systems is the concept of continuous improvement. Continuous improvement requires performance evaluation to determine if goals are being met and if improvements are occurring. Permanent, transparent, and verified performance provides a true measure of improvement. Linking performance measurement and environmental systems globally across an organization's sites helps build broader environmental continuous improvement measures.

Many other internal activities related to production and operations potentially influenced by blockchain technology relate to other supply chain activities, including eco-design, material handling and flow, and supplier management, as examples. We delve further into eco-design and LCA initiatives.

3.6. Eco-Design and LCA

Eco-design is a particularly interesting blockchain use case that can be discussed as part of the production and operations or marketing stages of the supply chain. It involves multiple supply chain partners and functions within an organization. Eco-design, with a focus on new product development with environmental criteria playing a prominent role, is influenced by a blockchain in numerous ways. The blockchain helps with easily disseminating information to multiple parties involved, gathering and verifying information, controlling the environmental quality of materials, time management for new product development projects, and coordinating participants.

In some eco-design systems, the environmental impact of materials used requires validation. In some of these cases, specific tests need to be completed. For example, in the cradle-to-cradle design model, hazardous material weighting schemes are used for various materials. This information can be easily stored and accessed by multiple partners after a verification process. This practice is quite suitable for blockchain technology, where scalability concerns related to high volumes of transactions would not be characteristic for materials verification. That is, this process requires time and a limited number of verifications will be required. Once these materials are verified, they would be available for trade and marketing.

Materials will require verification and processing. Green process design is as important in eco-design as in green materials. These green processes require verification and improvement. Internal processes, through ISO 14001 aspects, EMS management can be improved, evaluated, and validated. External processes, potentially through a supply chain blockchain linkage of environmental management systems, will also need verification. These environmentally sound manufacturing process designs and improvements can be used with sourcing, supplier development, supplier selection, and operations management activities.

Eco-design systems integrated with LCA benefit from information accuracy. LCA materials inventory and impact constantly change with many uncertainties [33,34]. Significant environmental information uncertainty exists for these systems. LCA tools may have different foundational information, different levels of granularity, missing data, and even inaccurate information. To address some of these uncertainties, various simulation tools have been proposed to complete a sensitivity analysis, as demonstrated by Mueller et al. [34]. Blockchain validity, reliability, and transparency can reduce information uncertainty, providing better modeling inputs and outputs for eco-design and LCA tools.

Information standards based on product data technology standards for LCA data have been proposed [35]. Expanding these arguments to blockchain, as an information delivery vehicle with appropriate models developed, is natural. The same benefits derived from using these industry standards and protocols occur through blockchain technology and systems, especially with an overall goal of reducing LCA information uncertainty. Benefits for blockchain adoption for these design systems include: less time for LCA data collection; improved data quality; traceability of the data source; using actual data from suppliers, not from a generic source; and storing environmental information of a product through the end of life to better manage its recycling and disposal [18,36].

3.7. Outbound Logistics and Marketing

Downstream green supply chain activities include distribution and various customer management activities such as green marketing and packaging. Transportation, similar to inbound logistics, is a large concern for distribution channels. Distribution transportation planning is typically planned by the organization's outbound logistics systems. This may or may not include third-party logistics providers. As mentioned in inbound logistics planning, certification and verification of environmental and social performance concerns exist in this activity; blockchain processes can address these issues. Information sharing on blockchain technology reduces the required paperwork, supporting validation requirements, and prevents data manipulation and counterfeiting within logistics and transportation processes [29].

Similar to the blockchain contributing to the sharing economy associated with crowdsourcing warehousing, which applies to outbound logistics, there are transportation ride sharing activities for commercial transportation. Whether it is rail, trucking, or even light vehicles, the "Uberization" of commercial transportation is also occurring. In these cases, excess freight vehicle capacity can be managed through blockchain activities including authentication of drivers and vehicles to payment through tokens. Ridesharing achieves efficiencies in utilization of vehicles, lessening waste. Authentication of green practices and vehicles increase transparency to customers of transportation sharing.

Packaging can be reused and traced; in this example, blockchain traceability can extend the packaging material life through more efficient management. Recyclable packaging can be monitored and managed more effectively as well. With this monitoring, further confirmation of socially responsible packaging can occur. In an application released by the U.S. Patent and Trademark Office (USPTO), Walmart describes a "smart package" that would include a device that would record information on a blockchain regarding the contents of the package, its environmental conditions, its location, and more. Additionally, multinational supermarket chain Carrefour is already using a similar system where customers can scan packaging for detailed information on a product's source, production processes, and environmental characteristics.

Building packaging with blockchain information transparency can improve green marketing efforts. According to green marketing theory, consumers are more likely to purchase greener products if they are confident that the product is actually green [37,38]. This confidence increases with the transparent, verified, and immutable information from blockchains. Overall, substantial green consumer implications exist due to blockchain technology. Two examples of these blockchain activities are consumer token incentive systems to purchase green and product tracing for returning of end-of-life products by consumers. Substantial green consumer theories, including social confirmation theories to perceived behavioral control, can be used to explain the blockchain benefits for green consumer behavior and action [38].

3.8. Waste Management

Organizational waste management along the supply chain is critical to many sustainable supply chain activities. Waste minimization is the ultimate goal for organizations and supply chains. However, if waste is generated, then tracking is critical for reasons related to the circular economy and industrial symbiosis. It may also be critical from the perspective of waste disposal and potential liabilities associated with disposal.

For waste minimization purposes, smart contracts can be used to ensure waste is minimized across the supply chain. Performance criteria for suppliers for waste reduction metrics can be included in smart contract execution agreements. Metrics and management around hazardous wastes, such as those identified by the toxics releases inventory (TRI) [39], can be tracked. Specific levels may be dictated in smart contracts for acceptable performance. The waste minimization angle may be to adjust and update smart contracts as part of a continuous improvement process for supply chains. Similar to carbon trading, waste trading can also be managed.

When minimization of waste is not possible, then there are opportunities to environmentally and sustainably manage this waste. One method of accomplishing this goal is to identify how and where the waste can be used to make it a by-product or to minimize its environmental impact. Waste exchanges have been utilized for effective industrial symbiosis realization, expanding the scope from local to national levels [40]. One especially cogent application, not typically considered, is the exchange of construction waste from the construction supply chain. In the construction case, there is a strong argument for 'buildings as material banks', which can be effectively managed through blockchains and the Internet [41,42]. More on this issue in terms of traceability and verification are described in the reverse logistics discussion.

Many times, eliminating waste completely from the supply chain is impossible. When this occurs, sustainably managing the waste is required. In this situation, the waste management supply chain processes need to be managed and risk plays a significant role. Risk is especially pertinent when managing hazardous wastes, which is also an expensive undertaking. In the United States, the tracking of hazardous wastes is critical due to the long term possibility of becoming a potentially responsible party to superfund sites. This means that companies or even supply chain partners may be responsible for significant multi-million dollar cleanup costs associated with poorly managed landfills and company sites. Having a permanent record and tracking waste disposition can help manage these liability concerns. It may be valuable for government agencies for tracking responsibility of waste as well. There are a number of dimensions of waste management blockchain capabilities and limitations that have been reviewed [43]. Fraud and manipulation, wrong or loss of information, manual processing, lack of knowledge about technology, and lack of control are all concerns for waste management in this environment.

3.9. Reverse Logistics

Reverse logistics are necessary for a number of take back regulations and building remanufacturing capabilities. One of the major concerns with remanufacturing and reverse logistics planning is the uncertainty in the location and supply of material at their end-of-life. Knowing the location of a material (i.e., traceability) to be taken back or remanufactured can help reduce uncertainty in the materials. Regulatory policies, such as the waste electrical and electronic equipment (WEEE) requirements, state that original equipment manufacturers (OEMs) are responsible for their goods. Thus, traceability of materials in the supply chain, as well as authentication that the material belongs to a particular OEM, improves the efficiency of the process for managing return flows. Mandated producer responsibility through regulations is one aspect; voluntary extended producer responsibility and product takeback can benefit from transparency, traceability, and authentication.

Similarly, circular economy practices have at least four levels of value recovery including product-life extension, reuse, remanufacture, and recycling [44]. Other than tracing materials, as identified above, one aspect of the blockchain that may be important is the terms of exchange. Smart contracts may be set up where the financing of returns can be completed electronically. In this case, instead of transferring products and materials, some form of payment is required it is not possible to manage the actual finances. Payment may be based on the quality of the material, which can be traced by data, but also the history of the cost of the product or material. Together, these items can be evaluated and payment can be completed through blockchain payment systems.

The payment scheme is critical to attracting enough product or material to drive the product through the system. Some circular economy principles do not necessarily require that a product or material be at the end of its life, but that it is returned in some condition level. Having this information, such as the number of recycling cycles, or purchase date of a product, assist in determining values. Once the value is determined, the payment can be completed. The payment location may be critical as well. Since globalization of supply chains will continue, paying for the product or material, no matter where it exists, can be more easily completed using cryptocurrencies whose values can be based on local currencies. This supply chain finance application of blockchains along with transparency can enable circular economy practices.

3.10. Energy

Energy is an important resource for all supply chain activities and managing energy is central to greening a supply chain. Sustainable energy management typically has environmental relationships associated with air emissions, fuel resource usage, and issues such as biodiversity and hazardous materials emissions. The amount of energy required to run blockchain technology can become overwhelming, especially if there is a need to solve algorithms for solving hashes as part of smart contracts. It is not clear if mining will be necessary for supply chain activities and blockchains.

Distributed storage and operations will require significant energy requirements for electronic databases; as redundancies in data storage will potentially cause exponentially greater energy needs.

Energy-related blockchain activities may support supply chain sustainability. Some organizations and supply chains, in order to achieve zero greenhouse gas emissions, use carbon credit markets for carbon offsets. These markets have been controversial given the difficulties in tracing the location and validity of the offsets. Calculation and the additionality requirements have made them controversial [45]. Improving transparency and clarity of a carbon credit can be effective using blockchain technology trust mechanisms. Also, not all carbon credits are created equal. For example, a carbon offset credit generated from a solar farm in a developed country may not have the same total environmental and sustainability of a carbon offset credit from an environmentally sensitive and poorer nation. In the latter situation, there may be more environmental co-benefits such as biodiversity management and offering poverty alleviation opportunities.

Internal emissions trading mechanisms for supply chains can also be better supported through transparency and information sharing from blockchain technology. This type of trading can provide financial benefits for energy use reduction by trading credits. Part of the trading and incentive mechanisms can be financially supported through cryptocurrency exchange [46].

Another example of energy-related blockchain improvement for supply chains is related to decentralized energy management within and between supply chain partners or communities. Rooftop solar power can be more accessible and economically feasible, further supporting adoption of renewable energy. Digital wallets as rewards may be one avenue for incentivizing employees and organizations to adopt more renewable energy along the blockchain. Expanding neighborhood blockchain-enabled micro-grid trading of solar energy to the supply chain, such as that supported by LO3 Energy, can provide certifiable and greener energy.

4. Research Concerns

Blockchain is a revolutionary technology with the potential to challenge supply chain processes and thought. Some research is required to understand the barriers, enablers, and diffusion of this technology [47]. Additionally, research related to the influence of blockchain on sustainable supply chains at organizational strategic and operational levels, its supply chain, broader industry networks, and the macro-economy are all needed.

The research domain is quite broad for a technology that may prove disruptive to the status quo of practice. We will not delve deeply into each of these research questions, but only provide a general set of issues that require investigation. The research on blockchains, sustainability, and supply chains is in its infancy with the academic field fertile for sowing ideas, theories, and analysis; many of which will grow [48]. For example, Francisco and Swanson [18] developed a conceptual model that incorporates the theory of acceptance and use of technology. This framework addresses the intentions in the use of blockchain technology for supply chain transparency.

As we are in the early phases of blockchain, adoption and diffusion of the technology is a general concern. Diffusion theory and technology acceptance models may require direct and explicit accounting for multiple stakeholders in acceptance of the diffusion. Multiple agents are involved in the adoption and agreement to be involved in the technology. Sustainability has heterogeneous meanings to participants in a supply chain. This heterogeneity and the need for blockchain may either hinder or aid diffusion. It can hinder diffusion because not everyone will agree that investment in such a technology would help with sustainability. It may be an enabler, since supply chains and partners may seek greater homogeneity and standardization of sustainability. Thus, the role of sustainable supply chains and philosophies and practices can play differentiating roles. Studies on what factors and constructs play a role in barriers or enablers are required.

Company, industry, product, and competitive environment characteristics may each influence the adoption of blockchain technology for sustainable supply chains. For example, in industries with a poor reputation, there might be greater adoption of transparency-based blockchains to support sustainability in supply chains. In this situation, legitimacy building and theory help supply chain participants address reputational issues. Similar issues based on other traditional supply chain characteristics, including building trust, opportunism, and relationship management, can play a role based on the context. Revisiting the various organizational theories for green and sustainable supply chains [49] will be necessary. Competing theories or joint theoretical perspectives are required. For example, will information technology theories such as structuration and internal organizational adoption be more important than technology acceptance and diffusion theory be better predictors?

The theory and research necessarily need to be interdisciplinary and multilevel. For example, the issues of various boundaries and boundary spanning aspects of the research (see [50]) in supply chains are vague. The boundaries and constraints of green and sustainable supply chains include economic, organizational, cultural, technological and proximal boundaries. Whether these and/or other boundaries play a role and where we draw the boundary for blockchain technology and sustainable supply chains becomes a research question related to the impact, effectiveness, performance, and general capabilities.

An overarching question in each of these general research areas is whether blockchain technology is idiosyncratic, unique, disruptive, or just another incremental technology following the status quo rules. Do blockchain technology and the blockchain environment follow similar rules as other supply chain technological and process innovations? In other words, how can adopting blockchains be compared to current information technologies such as enterprise and supply chain wide resource planning systems? Additionally, how can blockchain technology be integrated into the current legacy information systems in the supply chain? The applicability of the current supply chain theories in the blockchain domain is a concern. From an epistemological perspective we are arguably at the level of idealism, where the empirics of blockchain technology have yet to become reality. There is currently much hype and hope associated with blockchain technology where its justification is based primarily on faith and it is uncertain whether this hype and hope result in true verifiable and empirical outcomes. What we have posited in this section is a rationalistic argument that theory and empirics need to be applied collaboratively to evaluate the idealistic notions of blockchain technology and sustainable supply chains conjectured in this manuscript.

5. Limitations and Conclusions

Actual and potential blockchain sustainable supply chain use cases and applications are extensive. We have only skimmed the possibilities of blockchain application depths; as new technology, knowledge, and needs arise, more use cases will follow. Significant additional possibilities exist. The hype and potential profits associated with blockchain technology provide substantial creative motivation to identify numerous future applications.

Disruptive technologies tend to follow the 'technology mudslide hypothesis' [51]. That is, coping with relentless technological change is analogous to climbing a mudslide raging down a mountain. Practitioners and researchers are scrambling to make sense of blockchain technology, where even stopping to take a breath can bury an individual or organization. Incorporating sustainability and supply chains is like adding boulders of different shapes and sizes to this proverbial technological mudslide. In this paper, we attempted provide an overview of the potential of blockchain technology in the sustainable supply chain context.

Admittedly, we have only scratched the surface of the roles that blockchain can play in sustainable supply chain management. Our primary focus was identifying potential uses across the spectrum of green supply chain management functions and activities, specifically on environmental sustainability in the supply chain. Our examination has significant extensibility to social sustainability, and some of this was made explicit in our discussion.

Given the more pragmatic perspective of this manuscript, we only briefly touched upon broader theoretical and philosophical concerns of blockchain technology in sustainable supply chains. A complete and detailed theoretical research evaluation of sustainable supply chain blockchain technology is still required, but true empirical and theoretical evaluation will mature as adoption matures. Moving beyond the hype and hope is necessary for rational determination of effectiveness.

The final thought we present is whether blockchain technology is a true disruptive social innovation, or is another affectation of incremental technology with limited strategic significance for sustainable supply chains. This question remains to be answered.

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