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► **To cite this version:**

Vincent Carrières, Andrée-Anne Lemieux, Robert Pellerin. Opportunities of Blockchain Traceability Data for Environmental Impact Assessment in a Context of Sustainable Production. IFIP International Conference on Advances in Production Management Systems (APMS), Sep 2021, Nantes, France. pp.124-133, 10.1007/978-3-030-85874-2_13. hal-04030424

HAL Id: hal-04030424

<https://inria.hal.science/hal-04030424>

Submitted on 16 Mar 2023

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Opportunities of Blockchain Traceability Data for Environmental Impact Assessment in a Context of Sustainable Production

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Abstract. Supply chains face various challenges for collecting reliable, transparent, and up-to-date data due to their increased complexity and globalization. This threatens their sustainability and limits the efficiency of environmental impact assessment of products with Life Cycle Assessment (LCA) methodology. This paper explores the opportunities, limitations, and research paths for assessing products' environmental impact using blockchain-based traceability data based on a systematic literature review. Results showed that blockchains are mainly used for product traceability and could be further used for the environmental impact assessment of products. A first architecture model and integration framework was proposed in the literature for the integration of blockchain-based LCA systems. However, the maturity of blockchain and supply chain organization are the prevalent barriers to implementing these systems. Further research is essential to shape these first results with strong opportunities identified .

Keywords: Blockchain, Traceability, LCA, Environmental Impact, Sustainability, Literature Review

1 Introduction

In recent years, sustainable production became a priority of industrial companies, guided by the Sustainable Development Goals (SDGs) of the United Nations that materialize 17 goals to achieve by 2030 [1]. The quest for environmental sustainability is mainly focused on reducing industrial emissions that have a persistent impact on the environment, such as global warming or ozone depletion, and ensuring the use of renewable resources [2]. Therefore, there is a strong need to access tools that can measure the environmental impact of industrial activities [3].

Life Cycle Assessment, one of the most widely used methods for assessing the environmental impact of a product during its whole life cycle [2], largely contributed to the acceleration of an environmentally sustainable production [4]. This methodological framework is divided in four main steps: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of results. LCA

studies can be used by industrial practitioners to identify the environmental "hotspots" of their production and to make decisions on the supply chain organization and product design [4] or to communicate the product's environmental impact to consumers [3].

However, although they can contribute up to 90% of a company's environmental impact [5], sustainable supply chains are hard to operationalize due to their increasing complexity and globalization[6], with difficulty ensuring traceability, transparency [7], accountability, and managing risks [8, 9]. The lack of knowledge of the suppliers' practices limits the environmental impact measurement and management [5]. Moreover, they heavily rely on centralized information systems with risks of single-point failure [7, 8] and the lack of information sharing across supply chains is not adapted to their dynamic nature [10]. These challenges faced by sustainable supply chains considerably affect LCA results' efficiency [3] with difficulty collecting available and reliable data [2]. Up to 70 to 80% of the time and resources for a LCA project is allocated to data gathering [1]. Data quality and integrity problems affect the reliability of the LCA results [2, 3]. Moreover, the temporal evolution of the environmental impact of industrial activities is significant [11] and requires conducting dynamic LCAs with up-to-date data [1].

To tackle those challenges, blockchain technology has been presented in recent scientific literature as a robust solution for establishing an efficient decentralized traceability system [12] by recording reliable, accountable, and up-to-date data across supply chains. In this context, the number of successful blockchain-based traceability platform case studies grew exponentially [13]. Despite the evident possibilities that blockchain traceability platforms offer to improve LCA conduction, there is an extensive research gap in the domain, with very little prior research done to evaluate the opportunities and the limits of combining these technologies [3]. The objective of this paper is to cover the range of opportunities of blockchain for sustainable supply chains and environmental impact assessment, and to identify the barriers to its adoption in the industry based on a literature review. The following research questions (RQs) will be addressed:

RQ1: What are the benefits of blockchain technology for supply chains and how is it used for product traceability?

RQ2: How can blockchain-based traceability platforms help create sustainable supply chains and conduct environmental impact assessment of products?

RQ3: What are the current limitations and barriers to the implementation of blockchain-based systems in the industry?

The remaining of this article is organized as follows. First, the research methodology used to conduct the systematic literature review and the analysis framework will be described in section 2. Section 3 will cover the articles' main propositions, organized following the previously defined analysis framework. Finally, a general conclusion and a discussion about the future research perspectives will be presented in section 4.

2 Research Methodology

This paper proposes a systematic literature review about the potential use of blockchain traceability data for assessing the environmental impact of products. The research

methodology was carried out in four steps. First, a general query was realized on Google Scholar using the keywords ‘blockchain’, ‘traceability’ and ‘sustainability’. A total of 8770 articles were identified in the process. A preliminary analysis of these results permitted to refine the list of relevant keywords. The definition of inclusion and exclusion criteria of this systematic literature review was then based and adapted on two existing frameworks, classifying Multi-Criteria Decision Methods (MCDM) [31] and Machine Learning (ML) Algorithms [32] for sustainable manufacturing (SM). These frameworks describe three phases meant to cover all the aspects of MCDM and ML Algorithms in SM. The first phase of classification is to consider the aspects of sustainable manufacturing that are covered among environmental, social and economic aspects. In this study, only the environmental aspect of sustainability will be explored. The main barriers and enablers of SM regarding the environment will be included while the aspects of influencing factors, manufacturing strategies and performance indicators of SM will be excluded from this study. A technology assessment specific to blockchain and its benefits for SM will also be included in this phase. The second phase is to consider which techniques and models are covered in the review [31]. In the scope of our study, we only include blockchain traceability and LCA models. The use of ML algorithms, MCDM or all other technical or methodological enablers for SM are excluded from this review. Finally, the third phase of classification establishes which benefits of sustainability aspects can be included in a literature review [31, 32]. In this study, all environmental benefits will be discussed, including greenhouse gases (GHG) emissions, waste reduction, water footprint, and product quality.

After defining the inclusion and exclusion criteria of this study, a query was built for Scopus and Web of Science databases around the concepts of blockchain, traceability and sustainability: ABS (blockchain) AND ABS (traceability OR tracking OR trace OR assessment) AND ABS (sustainab* OR lca OR "life cycle assessment" OR footprint OR "environmental impact"). We then proceeded to two sortings. First, only articles published in scientific journals, conference papers, and conference reviews in English were considered. The subjects of health, immunology, veterinary, biochemistry, and dietetics were also excluded being too distant from our scope. This brought the results to 64 documents on Scopus and 58 on Web of Science. All remaining documents from both databases were downloaded and duplicates were removed. In the second sorting, articles were read, which led to the exclusion of papers following the inclusion and exclusion criteria defined in the previous paragraph. Also, articles discussing financial or energy trading applications were removed because they were not focused on the traceability of physical industrial products. Following this second sorting, 29 articles relevant to the scope of our study were analysed.

The presentation of our results is organized to address the three research questions formulated in the introduction. RQ1 will be tackled in section 3.1 with a presentation of blockchain technology and its benefits in an industrial context. Section 3.2 then focuses on the specific use of blockchain for the traceability of supply chains. To address RQ2, section 3.3 will draw the opportunities of blockchain traceability for ensuring the sustainability of supply chains. Section 3.4 will review the proposed frameworks and implementations of blockchain-based impact assessment models. Finally, section 3.5 will present the limitations and adoption barriers to the implementation of blockchain traceability in sustainable supply chains and give insight to RQ3.

3 Results

3.1 Presentation of Blockchain and its Benefits

The blockchain is a shared and distributed ledger composed of a series of data blocks, linked in a chain using cryptographic methods [14, 15]. This ledger acts as a decentralized database that records, in a secure and immutable way, every transaction that has been executed in the network [7]. Multiple copies of the ledger are shared with all the peers of the network, each node possessing a full copy of the blockchain updated in real time [16, 17]. Each data block includes at least the transaction data, the hash of the block, a timestamp, and the hash of the previous block [13]. Any attempt to corrupt a block's data would therefore create a cryptographic link disruption with the following blocks values [14]. Consensus algorithms are used to establish trust. Before being recorded, each transaction is verified against the ledger's current state, ensuring that all peers of the network agree on the network's current state [14, 18]. Smart contracts also set rules for processing the transactions without the need for a third-party intermediary [15].

The main benefit of blockchain is that it is virtually impossible to alter because all network peers keep all transaction data [16]. It ensures, at the same time, the immutability, integrity, anonymity, and persistence of the data recorded in it [5]. The decentralization of the network also allows easier access to data for all blockchain users [8] and the safeguards permit to enforce trust between users [14].

3.2 Use of Blockchain for Product Traceability and Certification

Supply chain traceability is a frequently discussed solution to sustainable supply chain issues [14]. In the last few years, blockchain-based traceability platforms have been successfully implemented in various sectors covering the fashion industry [14, 19], the mining sector [6, 19], the pharmaceutical industry [6], and most of all the agri-food industry [18, 20-22]. Indeed, blockchain technology's inherent characteristics such as auditability, immutability, and transparency are valuable assets for product traceability in these industries [23]. Firstly, blockchain-based traceability is valuable for sharing information and providing a technology-based trust among stakeholders, like in its application in the organic cotton supply chain [14]. Secondly, the digitalization of supply chains using blockchain technology is also developing in cobalt mining and pharmaceutical industries to increase operational efficiency [6].

However, the main applications of blockchain-based traceability systems can be seen in the agri-food industry to trace food quality [19] and build more agile supply chains. These systems considerably reduce the product's origin identification time and facilitate eventual recall [22], with authentic data recorded from sourcing to sales stages [20]. Therefore, blockchain traceability is suitable for the origin or quality certification of food products [23]. It also has several benefits for supply chains, such as improvement of collaboration and reduced economic loss or product waste [17]. Blockchain-based traceability platforms can also be coupled with IoT or RFID technologies that oversee data collection along the supply chain and allow full digitalization [21, 22]. Blockchain-

based traceability can also be used for communicating transparent information to the consumer about the origin of a final product [18, 21].

3.3 Opportunities of Blockchain for Sustainable Supply Chains

The huge potential of blockchain traceability that led industrial companies to use it for ensuring the quality, provenance, or safety of products can also be used to ensure the environmental sustainability of supply chains [17]. For example, a blockchain-based traceability infrastructure can monitor and trace flawed products accurately, decreasing the need to rework and recall [24] and therefore reducing resource consumption, generated waste, and GHG emissions [7, 17]. Blockchain platforms can also act as a monitoring system for the sustainable sourcing of raw materials [19] to avoid overexploitation and rational use of natural resources [10] by ensuring the provenance of data along the supply chain. They could also monitor and certify an ethical and sustainable production [25] by delivering transaction certificates proving the origin and quality of products, ensure that sustainable standards are being implemented across the supply chain [1]. Also, they could help businesses in managing the environmental sustainability performance of their activity [3] by providing robust indicators based on accurately corrected data and simplify sustainability reporting by making all necessary data immediately available and traceable. They could even help waste information management as part of a circular economy [26] and trace dangerous products and chemicals [17].

However, the foremost discussed opportunity of blockchain traceability for an environmentally sustainable supply chain is its ability to track the level of CO₂ emissions [27, 28] and the water consumption of a product during its entire life cycle [10]. The benefits and opportunities of blockchain traceability platforms for LCA data collection will be further explored in the next section.

3.4 Review of Blockchain-based Impact Assessment Methods

Blockchain traceability systems could help overcome the complexity of conducting an LCA by facilitating the process of data collection [2]. Blockchain would considerably help data acquisition, give an objective insight into the functional unit and enable the accounting of all possible inputs of complex supply chains [3]. Moreover, it would allow a more fine-grained and relevant impact assessment based on actual production data and real-time data [1]. Blockchain-based LCA would also be beneficial at the design stage for eco-conception.

With all these opportunities in mind, a framework for implementing a blockchain-based LCA and a system architecture were developed [3]. It consists of a blockchain traceability platform that collects additional environmental-related data (electricity consumption, waste emission...) in traceability transactions and integrates them in the LCA calculation. It is a multilayer system with data collection with IoT, a recording of data with blockchain, an impact calculation with LCA, and visualization of impact with big data analytics [3]. Therefore, blockchain serves as a bridge between data collection and big data analytics. Combining IoT, big data analytics and blockchain is an efficient

way to considerably reduce the cost and time of conducting an LCA [2]. It can also be integrated with ERP systems for even more efficient data collection [1]. Blockchain-based LCA systems could therefore automate the calculation of the environmental impact, save time and resources, and build consumer trust with the possibility to communicate real-time impact of products [3].

3.5 Adoption Barriers to Blockchain Traceability for Impact Assessment

Although blockchain-based impact assessment methods seem incredibly promising, they still face limitations due to blockchain's adoption barriers in supply chains. These implementation barriers are divided into four categories detailed in the table below [29].

Table 1. Classification of blockchain-based LCA adoption barriers

Types of adoption barriers	Challenges	Description	Articles
Technological	Scalability	Difficulty of blockchain to deal with a growing number of transactions.	3, 7, 16, 22, 29, 30
	Throughput and latency	Difficulty to deal with the large number of simultaneous transaction of a SC.	22
	Negative perception	Blockchain technology can be associated to cryptocurrencies, malicious activities and high-energy consumption	3, 7, 29
	Immutability	Recorded errors stay indefinitely on the blockchain	3, 7, 20, 29, 30
	Interoperability	Can be difficult to operate with other systems	16, 20, 26
Organizational	Cost for setup and maintenance	Especially the cost of data collection and the cost of the infrastructure in itself	1, 3, 7, 20, 22, 29
	Lack of managerial commitment	It might be due to a lack of knowledge of blockchain abilities	2, 7, 29
	Lack of expertise	Lack of technical expertise and knowledge about blockchain	7, 20, 22, 29
	Lack of tools for blockchain implementation	No standards or appropriate methods, tool or metrics available	7, 29
	Resistance to change	Hesitation and opposition to altering and replacing already existing systems	7, 20, 29
SC Inter-Organizational	Opposition to data sharing by stakeholders	Stakeholders might be skeptical or opposed to sharing their sustainability data with others	1, 7, 20, 29

	Problem of collaboration	Lack of communication and collaboration because of diverging objectives along the SC	7, 20, 29
	Cultural differences	Different organizational culture can hinder the adoption of blockchain	7, 29
External environment	Lack of governmental regulation	The absence of regulation can slowdown the adoption of blockchain	7, 20, 29
	Lack of external stakeholders' implication	NGOs and communities do not support blockchain technology	7, 29

The most significant barriers identified are the technological and supply chain environment barriers [2, 29]. Measuring the confidence level of data recorded on the blockchain is another issue [16, 20].

4 Discussion

There is undoubtedly a consensus in the literature that blockchain technology is booming and is prioritized for the digital traceability of industrial goods because of its inherent qualities. Many articles discuss case studies of successful blockchain-based traceability platforms in various industrial sectors and the general opportunities of blockchain-based systems for ensuring transparency, trust, and traceability in complex supply chains. However, the subject of using these blockchain-based systems for sustainability is still very limited in the literature. This approach seems very new, as the few papers on this subject were all published in 2020 or 2021. Although these articles are scarce, they all agree that blockchain's benefits for supply chain traceability can serve for monitoring sustainability and that blockchain-based traceability could encapsulate data about the environmental emissions and the use of resources of industrial activities.

To go further, the link between the concept of blockchain technology and the concept of LCA is still largely unexplored, with only three existing articles. Moreover, this research path remains very conceptual, constituting a large research gap between the theory and the field ability to implement a functional and robust system on a large scale. Only one paper proposed an implementation framework and system architecture, while the others only listed the benefits of blockchain-based LCA. With these three articles, blockchain-based LCA systems' technical feasibility was demonstrated, and the benefits and adoption barriers were clearly identified.

Future scopes of research are numerous. First of all, although a first framework and architecture of a blockchain-based LCA system was developed, it clearly lacks a methodology to implement the system. Future research focusing on an implementation process identifying the stakeholders, their roles and relations, the deliverables of the project and addressing the problematics identified in section 3.5 would be an important contribution. Another research opportunity would be to develop a Proof of Concept of a blockchain-based LCA system in an industrial supply chain to prove that it is

applicable and integrable and to provide feedback from a case company before full-scale implementation. Based on an already blockchain-traced supply chain, the traceability data model's extension to include data related to the environmental impact, and the integration of the traceability platform with an LCA calculation software and big data analytics represent also interesting opportunities. The possibility of integrating an interface to this system for the final consumer to have access to an up-to-date environmental impact of a product based on real production data via QR code, for example, could add value as well. Finally, another scope of study could be a literature review covering the benefits of blockchain for the two other pillars of sustainability : social and economic.

5 Conclusion

In conclusion, this article's contribution was to shed light upon the opportunities, limitations, and possible research paths on the use of blockchain traceability platforms for the environmental impact assessment of products by exploring the existing literature. The originality of this paper is to focus specifically on blockchain-based LCA concerning all the above-mentioned aspects of their conceptualization and implementation. New paths of research have also been unveiled in the discussion section. The implication of this literature review is therefore to help the future development of blockchain-based LCA systems by practitioners and researchers by proposing an overview of the current state of research on this topic and by synthesizing all knowledge related to the benefits and difficulties of their implementation. This was done facing the already proven benefits of blockchain traceability for supply chains in general with the current limits of sustainable supply chains and impact assessment methods. This literature review however faces a few limitations. First of all, blockchain-based LCA models are not discussed in the scope of this study and are only briefly presented in section 3.4. This study therefore remains a theoretic contribution to the subject and does not propose any system implementation. Also, although a systematic literature review methodology was applied, we acknowledge that this paper is not a full picture of the blockchain-based LCA subject as it considers only peer-reviewed journal papers, conference papers and reviews. Blockchain-based LCA pilot projects in the industry are for example not covered. A future scope of research could be a literature review overcoming these limitations.

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