Blockchain technology in life cycle assessment: opportunities and current challenges

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Abstract: The large-scale adoption of life cycle assessment is limited by several barriers, among which is pivotal the difficulty in collecting reliable data. Background data are often outdated, while the collection of foreground data represents a difficult and time-consuming activity. By allowing the decentralized, systematic, and standardized collection of data and by guaranteeing storage and traceability in a transparent and tamper-proof way, Blockchain technology could represent a practical solution to the above-mentioned barriers. Hence, the present study aims to shed light on the benefits the application of blockchain technology might bring to the LCA field. Moreover, the paper points out the challenges that characterize blockchain adoption in LCA analysis and provides suggestions on future research to overcome these challenges and facilitate the penetration of the technology for LCA purposes.

1. Introduction

Life cycle assessment (LCA), allowing the environmental impacts of products and services to be assessed holistically, is a pivotal tool to achieve the sustainability objectives set with the 2030 Agenda for Sustainable Development. Despite its potential, LCA application is nonetheless severely limited by a series of barriers. Most of the LCA requirements in terms of costs and time are related to the collection of primary data in the inventory phase (Teh et al., 2020; Mieras et al., 2019), with increasing costs as the amount of data needed increases (Teh et al., 2020). LCA results are reliable only when quality data is collected (Von Bahr and Steen, 2004). However, this is made difficult due to the need to take inputs and outputs from different actors along the supply chain (SC) (Zhang et al., 2020; Liu et al., 2020). Despite attempts to collect data directly from suppliers (Shojaei et al., 2019), transparency of the assumptions and data quality can often be questioned (Shojaei et al., 2019; Teh et al., 2020). The above, combined with the actual design of databases, centralized and internal to individual firms, and the lack of incentives for the latter to share data (Liu et al., 2020), make it necessary to repeat the collection of primary data for each different study (Davis et al., 2010). As a consequence, a limited number of products is present in the databases and the related data are not necessarily exhaustive (Shojaei et al., 2019). To fill major data gaps, estimates or average values are introduced into the analysis, further reducing data reliability (Teh et al., 2020). On the other hand, secondary data are often not sufficient to compensate the lack of necessary data (Teh et al., 2020) or are outdated (Mieras et al., 2019). To overcome these issues, it would be appropriate to increase standardization in data collection, which however is difficult to achieve given the strongly decentralized nature of the SC system

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(Zhang et al., 2020). Audits by a third party could help to improve the robustness of LCA analyses but would also lead to higher complexity and cost (Teh et al., 2020).

Blockchain technology (BT), by introducing a decentralized, transparent, and immutable database, could make the LCA process more inclusive and reliable, also increasing the granularity of available data (Shojaei et al., 2019). Various applications of the technology to LCA analysis have been proposed in the literature; however, they entail different perspectives and heterogeneous objectives. Hence, the present study aims to provide an overview of BT (Section 2) and its applicability in the LCA field (Section 3), highlighting the benefits coming from its adoption (Section 4). In addition, Section 5 points out the many challenges BT should overcome to be extensively applied in LCA and possible solutions. Conclusions and ideas for future research are then presented (Section 6).

2. Blockchain technology overview

BT is defined as a particular type of distributed ledger technology (DLT), characterized by encryption and verification standards (Tapscott and Tapscott, 2018a). The data present in the ledger is included in block structures chained together through cryptography and hashing techniques (Schletz et al., 2020).

Being a ledger distributed across participants in a network, decentralized consensus mechanisms allow for the creation of blocks and the reaching of the agreement on the correct status of the chain, ensuring the existence of a single blockchain without the existence of a central authority (Konstantinos Christidis, 2020). There are several consensus mechanisms, as proof of work (POW), proof of stake (POS), proof of Authority (POA), etc. – for details (Andoni et al., 2019). The BT is characterized by the following properties: decentralization, as each node has a copy of the blockchain, with the possibility to read or add information in a decentralized way (Zheng et al., 2017); persistency and immutability as it lacks a central point of failure: to delete the database, the individual databases owned by each user of the network should be deleted (Zheng et al., 2017), making it de facto permanent and also taking control of the network for data tampering would result in a higher cost than the benefits obtainable - for details (Tapscott and Tapscott, 2018a); security, as it uses asymmetric cryptography mechanism to validate the authentication of transactions (Zheng et al., 2017); automation, as through smart contracts it is possible to automate transactions among players, facilitating their management especially (Pauw, 2018); transparency and auditability, as the decentralized nature ensures data visibility and reading, facilitating the analysis by external stakeholders and increasing trust (Zheng et al., 2017).

The properties are however moderated, among the others, also by the specific type of blockchain, namely: (i) public - each person can read, interact and participate in the network consensus mechanism; (ii) fully private - participation must be guaranteed by a centralized body reducing, in fact, decentralization (Buterin, 2017); (iii) consortium - aggregation of several entities, as financial institutions, positioned between the public and the private one (Buterin, 2017). Table 1 reports the features of the different types of BT.

Table 1. Main differences between public, private and consortium blockchains, based on Albrecht et al. (2018), Buterin (2017), Edeland and Mörk (2018) and Sedlmeir et al. (2020).

	Public	**Private**	**Consortium**
Access - read	Permissionless	Permissioned; permissionless	Permissionless; Shared Permissions
Access - write	Permissionless	Permissioned	Shared Permissions
Personal information	Pseudonymity	Known	Known
Governance	Decentralized	Centralized	Partially decentralized
Consensus mechanism	Influence based on scarce resources (e.g., POW, POS)	Influence not based on scarce resources (e.g., POA, PBFT)	Influence not based on scarce resources (e.g., POA, PBFT)
Security	Decentralized	Single failure point	Various
Transaction speed	Depend (low if POW)	Rather high	Higher than public
Energy consumption	Depend (high if POW)	Rather low	Rather low
System costs	High	Rather low	Rather low
Individual costs	High	Rather low	Medium to low

3. Blockchain applicability to LCA

The current maturity of BT led to the constant growth of its consideration by the industry, and BT is now among the top 5 priorities of firms (Brodersen et al., 2019). The general enthusiasm towards BT led nonetheless to its application also in contexts not requiring it. Particularly, as the efficiency of a decentralized database is rather low (Sedlmeir et al., 2020), its applicability's needs should be carefully evaluated before opting for it. Numerous decision-making frameworks were designed, highlighting the characteristics an application should entail to request the adoption of the BT (see Zhao (2019) and Samarakoon (2018)). To confirm BT's applicability to LCA, this paper refers to the framework in Table 2.

Table 2. Framework for the evaluation of the applicability of BT to LCA, based on Krofak (2019), Franke et al. (2020), Wang et al. (2016), Schletz et al. (2020).

Feature	**Blockchain usability**	
Network of participants with different interests?	✓	-
Knowledge and trust among contributors	✓	Not necessarily, but required trust in uploaded data validity
Aim to remove intermediaries	✓	Possible for SC intermediaries
Working with digital assets	✓	LCA data
Create a permanent authoritative record of digital assets	✓	-
High-performance and rapid transactions required	✓	-

Store of large amounts of non-transactional data required	✓	Not necessarily
Transactions created by different participants mutual dependency	✓	Multiple steps of the value chain are processed by different actors
Need/will rely on a trusted party	✓	Possibly not to reduce costs and complexity
Manage contractual relationships	✕	-
Shared write access required	✓	Multiple suppliers in the SC
Shared read access required	✓	Clients in the SC
Time-sensitive Interactions	✓	Benefits from data gathering time reduction

4. LCA benefits from adopting blockchain technology

We employed a non-systematic search and a narrative review for the analysis of the literature. The considered academic (journal articles, conferences, books, chapter) and non-academic contributions (grey literature) referred to both BT and LCA; given the limited scientific maturity of the area, we also allowed for the integration of sources dealing with the broader concept of sustainability.

According to the literature, the application of BT could improve the efficiency and effectiveness of LCA (Farooque et al., 2020). The benefits provided are analysed based on the technology characteristics and according to data collection, analysis and use.

In the data collection phase, the first advantage brought by BT is the possibility to allow decentralized data collection and writing along the entire SC (Shojaei et al., 2019). This simplification of planning reduces the time and costs of data collection and the administrative structure necessary for database management (Teh et al., 2020) and allows for a greater level of detail and capillarity of information, beside increasing the product types registered in the database (Shojaei et al., 2019). In the energy sector, BT could improve the energy management (Mengelkamp et al., 2018), allowing to track besides the consumption also the source of energy used in each step of the life cycle of a product and therefore the real impact in terms of LCA (Shojaei et al., 2019).

The introduction of coding of specific smart contracts during the data collection would allow standardizing the collection methodology, eliminating the products not presenting sufficient information (Shojaei et al., 2019). Smart contracts could also allow the automation of data collection by combining BT with other Industry 4.0's technologies, such as Internet of things (IoT) (Zhang et al., 2020), or with ERP systems or SCADA (Teh et al., 2020), thus introducing the concept of industrial blockchains (Liu et al., 2020). Several examples can be found: Shakhbulatov et al. (2019) make extensive use of sensor systems (e.g., GPS sensors to track the path of the trucks and calculate automatically their emissions) connecting the different phases of the product life cycle; Aoun (2020) refers to smart meters for measuring energy flows in the energy sector; Mieras et al. (2019) stress how a BT-IoT binomial would allow keeping the data collection time fixed, while also increasing the amount of data collected and eliminating the need for external auditors, leading to reduced complexity and cost (Saberi et al., 2019). Finally, thanks to the transparency and accessibility of the information contained in the blockchain, standards referring to various sustainability factors linked to the different phases of the SC could be strengthened and further verified. All in all, the application of BT could improve the ethical behaviour and accountability of the actors involved (Teh et al., 2020).

The data analysis phase can benefit from the adoption of a common methodology for the data collection as well. Such a methodology would indeed guarantee homogeneity and reliability of the results (van der Meer, 2018), thanks to the reduced need for relying on hypotheses (Teh et al., 2020) or not updated background data (Mieras et al., 2019).

A decentralized system would also favour the data search and reading, eliminating the need to refer to the centralized database of each company and reducing the level of resources dedicated to the activity (Liu et al., 2020). Moreover, BT guarantees data credibility (a manipulation of data would lead to a change in the hash of the block) (Sedlmeir et al., 2020). Data traceability is guaranteed by the transparency of BT, and this increases the end-user's perception of reliability and usability (Teh et al., 2020). Additionally, thanks to standardized data collection and analysis, different solutions can be easily compared (Shojaei et al., 2019). The availability of a large amount of data for a single product could improve its conditions during the useful life through predictive maintenance practices (Liu et al., 2020; Shojaei et al., 2019), as well as during the recycling phase (Shojaei et al., 2019), reducing environmental impacts as consumption or pollution.

5. Challenges of blockchain adoption in LCA

Besides the proven benefits, challenges and limitations should be acknowledged. Several purely technical issues could arise. The BT trilemma of decentralization, scalability and security presents several trade-offs, as well as the binomial network scalability and the transactions speed does (Shakhbulatov et al., 2019). Several solutions are introduced in the market supporting a parallel increase in speed and scalability, as sharding, sub-chains, payments channels (Andoni et al., 2019). As LCA does not necessarily require high transaction speeds (Table 2), the specific issue is naturally reduced.

Data immutability poses the problem of verifying the correctness and truthfulness of the inputs (Peter, 2019). A possible solution to the use of trusted auditors entails the check of data reliability before their insertion through smart contracts (Gurcan et al., 2018). Additionally, sensors, artificial intelligence and big data analytics (Aoun, 2020; Schletz et al., 2020), could allow the real-time collection of data along the SC (Farooque et al., 2020).

Corporate data privacy issues might emerge from the management of LCA data through a decentralized system (Shakhbulatov et al., 2019), and this indeed represents a pivotal issue connected to information disclosure policies between partners in the SC (Farooque et al., 2020). Saving off-chain the sensitive data of a firm (Liu et al., 2020; Franke et al., 2020) offers a solution, while leaving on-chain only the hash of the data to grant data integrity (but not their immutability). Additionally, in a public blockchain, despite the participants are identified by an ID, it is possible to trace the transactions back to the real name (Konstantinos Christidis, 2020). Solutions in this regard range from the use of different IDs for each transaction to the introduction of sub-chains (Konstantinos Christidis, 2020), to the use of advanced cryptographic solutions, such as Zero Knowledge Proof (Tapscott and Tapscott, 2018a) or mixing (Zheng et al., 2017). As for LCA applications, a further technical limitation is represented by the impossibility of storing all the data, both for the size of the blocks (Liu et al., 2020), and as the chain would become too "heavy" (Aoun, 2020). A solution could be data aggregation (as monthly rather than daily data aggregation) (Aoun, 2020) or off-chain data storage, leaving only the hash on-chain.

The lack of mathematical libraries and the impossibility of introducing analysis and smart contracts that are not deterministic or not representing integers is a technical limitation at the computation level (Konstantinos Christidis, 2020).

From an LCA perspective, the BT electricity consumption represents a possible limitation (Smetana et al., 2018; Mengelkamp et al., 2018). However, different types of blockchains entail differences (Table 1). The electricity consumption of Bitcoin in 2020 is estimated between 60 and 125 TWh, comparable to the annual electricity consumption of Austria or Norway (Sedlmeir et al., 2020). If Bitcoin (i.e. a POW blockchain) were to reach the magnitude of a worldwide payment system, its emissions alone could push global warming above 2°C (Mora et al. 2018). As some authors disagree on this latter point (Sedlmeir et al. 2020), the POW blockchains' electricity consumption is widely recognized. Focusing on public blockchains, the energy consumption could be reduced by adopting consensus mechanisms other than POW, based on scarce resources other than the computational power: in POS the influence on the consensus mechanism is based on the scarce resource of capital, reducing the electricity consumption of many orders of magnitude. In small-scale consortia or private networks, where consensus is not reached based on scarce resources, the electricity consumption would be even lower, despite the redundancy of a distributed database would never allow to obtain the limited energy consumption of a centralized system – for details (Sedlmeir et al., 2020).

From an economic viewpoint, considering public blockchain, a higher level of security guaranteed by the size of the network would be paid in terms of particularly high transaction costs (Mengelkamp et al., 2018). The use of a private blockchain could partially solve the problem, although an additional cost for managing the server should be considered (Franke et al., 2020).

At an organizational level, possible issues emerge due to the lack of adequate corporate infrastructure for BT (Smetana et al., 2018), limiting its potential (Gartner, 2020). Another strong limitation is represented by the lack of support from management and the lack of organizational policies for using BT (Farooque et al., 2020). Internal skills and knowledge on BT could also lack, despite technology providers might represent a useful support (Farooque et al., 2020). Organizational issues also exist at an inter-organizational level, as lack of SC collaboration, communication, and coordination (Farooque et al., 2020).

At the regulatory level, the lack of interoperability among sectors (Peter, 2019) is a limitation for industrial adoptions, together with the lack of standards and policies (Tapscott and Tapscott, 2018b). Given the decentralized nature, it is not clear who should be responsible for decisions (Teh et al., 2020; Albrecht et al., 2018). A gap also exists between BT's and society's regulation (the former expressed through the code of smart contracts) (Tapscott and Tapscott, 2018b), but it could be easily overcome by defining smart legal contracts (Aoun, 2020).

Finally, from an applicative viewpoint, to allow for a standardized data collection it is necessary to involve the entire community (Mieras et al., 2019). The lack of external stakeholders' pressures and involvement is a strong barrier to the adoption of BT in LCA (Farooque et al., 2020). To date, this is a pivotal issue as empirical studies over practical applications are limited (Mieras et al., 2019).

6. Conclusions

Despite the undisputed advantages of the use of LCA, its pervasive application is currently severely limited by multiple problems related to the availability, reliability, and traceability of data. BT could solve these limitations, favouring the phases of data collection, analysis, and use. However, BT's characteristics and state of development impose some serious challenges which limit the current BT application to LCA. Future research is thus required to overcome the aforementioned technological limitations. Additionally, research should focus on the conduction of empirical case studies and pilot projects, shedding further light on the real implications of adopting BT to LCA.

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