


Review

Blockchain Technology in Life Cycle Assessment— New Research Trends

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Abstract: Environmental protection is currently one of the key priority areas of the European Union (EU). The search for precise tools to assess the impact of the economy, industry, or the production of individual products or services is crucial for an effective and efficient policy in environmental protection. Blockchain technology, originally related to the financial sector and cryptocurrencies, is an innovative solution that is increasingly being implemented by other areas of the economy and industry sectors. The authors reviewed the literature and based on it presented the possibilities and effects of using blockchain technology in Life Cycle Assessment (LCA), which is in line with the current development trends of this method. The analysis of the research conducted in this area also allowed to present not only the advantages of blockchain in LCA, but also the limitations of this technology and the potential directions of further research.

Keywords: life cycle assessment (LCA); blockchain; management; Internet of Things (IoT); Corporate Social Responsibility (CSR)



Citation: Karaszewski, R.; Modrzyński, P.; Müldür, G.T.; Wójcik, J. Blockchain Technology in Life Cycle Assessment—New Research Trends. *Energies* **2021**, *14*, 8292. <https://doi.org/10.3390/en14248292>

Academic Editor: Manolis Souliotis

Received: 30 October 2021

Accepted: 6 December 2021

Published: 9 December 2021

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1. Introduction

Environmental protection, rational management of natural resources, and inclusion of the ecological account in the economic account are among the contemporary priorities of the European Union in implementing the sustainable development policy. On 14 July 2021, the European Commission (EC) adopted a set of proposals to make the EU's climate, energy, transport, and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Achieving these emission reductions in the next decade is crucial to Europe becoming the world's first climate-neutral continent by 2050 and making the European Green Deal a reality [1]. One of the answers to the priorities of environmental protection contained in the EU documents is the remodelling of the rules for determining the actual cost of production or services, including calculations of all costs related to the production of goods and services along with their disposal—which corresponds to the ISO 14001: 2015 standard [2]. The guidelines of ISO 14001: 2015 are the basis for a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service, known as Life Cycle Assessment (LCA) [3]. Estimating the costs of production and use of a product based on the LCA method means taking into account the impact on the environment, society, and economy throughout the entire life cycle of the product. The LCA method considers the costs of using raw materials, the costs of material processing, maintenance, use, and final disposal or recycling [4]. Linking the LCA assessment with the ISO 14,040 series standards allows for the recognition of the cost of item production according to the following methods:

(1) cradle-to-gate: from the extraction of raw materials and transporting them to the factory, (2) cradle-to-grave: from raw material extraction, through use and disposal of the product and (3) gate to gate: from one defined point to another on the product life cycle axis [5]. Growing awareness of business responsibility, the need to implement environmental standards, or rationally managing resources are just some of the “motivators” to look for solutions that, on the one hand, meet environmental protection requirements, and, on the other hand, reduce consumption costs and increase the economic efficiency of production or service processes. In this area, blockchain technology is becoming more and more commonly and more widely used and supports the implemented business processes [6–12]. The question, therefore, arises whether blockchain technology can be used in LCA? Should the further direction of scientific research focus on linking these two research areas—blockchain and LCA? The aim of the authors was, based on the conducted analysis of the literature, to determine the current research trends in the area of potential blockchain use in LCA, but also to draw attention to its potential limitations.

2. Blockchain

Blockchain is a technology that is increasingly used in the modern world. Its creator is Satoshi Nakamoto, who in 2008 used this technology in cryptocurrencies [13]. The idea of blockchain assumes creating data chains between any two pages and storing them in a distributed cloud environment [14]. This technology is most often associated with cryptocurrencies, financial markets, or transactions, still, it is more and more widely used in other areas of industry or economy—health care, smart energy, copyright protection [15–20]. Originally blockchain technology was used to create a peer-to-peer network and focused on cryptography and smart contracts [21–23]. Illustrating the current, extensive range of blockchain technology use, one can use the visualization (Figure 1) developed by Casino et al. [24].

By reviewing the literature in blockchain and the possibilities of its use, Xu et al. [24] pointed to, emphasized by many researchers [11,25–30], a feature that enables the collection and processing of vast amounts of data in real-time. It is the fundamental advantage of this technology, which implies such extensive use. Hence, the financial area has become a natural sector for using this technology [31]. Two branches of blockchain use out of the possibilities of using this technology indicated in Figure 1 [24] relate to: economy and industry, as well as data management. The organization of production processes, supply chains, and warehouse management requires processing considerable information. This is another area that is within the scope of the possibility of adopting blockchain technology [32,33]. Other areas of blockchain application are: medical sector [34–41], education [42] or management and logistics [43,44]. Since, as many researchers emphasize, blockchain is primarily a kind of database [21,45,46], which supports the reading and transmission of data (information). It is based on a decentralized structure that allows direct contact of users without the participation of an intermediary and at the same time ensures the security of event logs with the help of the use of a time stamp [47,48]. The existing areas of blockchain technology use have focused on financial applications or the processing of large amounts of data, e.g., personal data in medical or insurance services. Bui et al. [49] by reviewing the literature in the blockchain area, they systematized and classified the research areas presented in the literature. Bui et al. divided the publications of research results by category into: inherent characteristics of a blockchain and add-ons to a blockchain. The first category includes publications that described blockchain features such as decentralization, immutability and transparency. In the second category, however, publications were grouped according to such features of blockchain technology as: authenticity, privacy, smart contracts, incentives and deployment.

Zhang, Y et al. [50] and Tang et al. [51] indicate a great potential in the integration of blockchain platforms with IoT, and thus the processing of a huge amount of data, which consequently fits into the assumptions of smart city and sustainable development. The main advantages of blockchain technology are: (1) the data that is stored on the blockchain

network is a rich source of information in itself, (2) blockchains can enable trusted data analytics environments to share data between multiple entities, adding an element of certainty to data and derived analytical models [51]. Bui et al. claims that the advantages of blockchain are based on a consensus mechanism. The authenticity of information in the chain is determined and verified by most nodes before it is encrypted in blocks. However, most of the existing research takes into account information from objective sources, and very little takes into account information from subjective sources. Researchers who consider such information do not propose an approach to verify its authenticity, and this remains a research gap.



Figure 1. Mindmap abstraction of different types of blockchain applications. Source: Casino, F.; Dasaklis, T.K.; Patsakis, C. A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telematics and Informatics* **2019**, *36*, 62 [24].

Therefore, as indicated by Xu et al. [24] the use of blockchain in the areas of IoT and Data Management can be linked and used in the LCA method? The authors point out that the existing literature lacks a guiding framework integrating Blockchain and other relevant technologies for carrying out LCA.

3. Life-Cycle Assessment

Dong et al. [52] (p. 4), while reviewing the literature, indicated the need to compare the environmental performance of buildings. The existing criteria have been developed based on: (1) the level of greenhouse gas emissions, (2) stages of the life cycle of a building, (3) absolute or relative value, (4) analysis of the entire building or its elements, and (5) top-down or bottom-up approaches (Hollberg et al. [53]) (see Table 1).

Table 1. Various types of benchmarks of LCA of buildings.

Category	Benchmarks	Description
LIFE CYCLE STAGES	Whole life cycle	Benchmark is a value for the whole life cycle of the building.
	Life cycle phase	Benchmark is a value for individual life cycle phases.
LEVELS OF VALUES	Lowest acceptable value	The limit value is defined as the lowest acceptable value.
	Present state of the art	The average or median values of the present state of the art.
	Best-practice value	The best-practice value that has been reached in building projects.
TOP-DOWN OR BOTTOM-UP	Top-down	Benchmarks are defined based on political targets.
	Bottom-up	Most of the existing benchmarks are derived from theoretical values.
ABSOLUTE OR RELATIVE VALUES	Absolute values	Benchmarks are defined as fixed values.
	Relative values	Internal benchmarks are defined according to a reference building.
WHOLE BUILDINGS OR BUILDING ELEMENTS	Whole building	Benchmarks are for the whole building.
	Building elements	Benchmarks are for the individual building elements.

Source: Dong, Y.; Ng, S.T.; Liu, P. A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review. *Building and Environment* 2021, 204, 108162, <https://doi.org/10.1016/j.buildenv.2021.108162>, [52] p. 4.

The literature analysis in question shows that the LCA method is increasingly used primarily in manufacturing industries. M. Buyle [54] and A.F. Abd Rashid and S. Yusoff [55] indicate difficulties in the direct use of LCA in construction due to the variety and mass use of materials, long product life cycle, and their enormous technological and urban diversity. S. Hellweg, L.M. Canals [56] and C.K. Anand, B. Amor [57] also emphasize the difficulty of using the LCA method in construction due to the huge amount of data and the inability to compare the tested objects, which is a significant problem when using the LCA method, especially when comparing buildings. This is a significant drawback of the LCA method, which in some cases may undermine the credibility of the obtained results. In order to carry out a systematic assessment of the impact of buildings, the emission levels should be analyzed quantitatively based on the impact analysis of each of the facilities tested. Therefore, each of the tested objects will be assessed separately, and its features will be taken into account, which is necessary for the interpretation of the environmental performance of buildings. Anand and Amor [57] indicate that there is still a research gap in this area, which makes it challenging to conduct a comparative analysis of buildings using the LCA method. Many researchers focused on reviewing the literature in the area of life-cycle assessment and its impact on the environmental assessment of buildings, which undoubtedly allowed to enrich and systematize knowledge in this area, which is an important step towards the elimination of the aforementioned barriers or problems with the use of this method. Khasreen et al. 2009 highlighted the importance of LCA as a decision support tool in the construction sector [58]. Ramesh et al. [59] performed a detailed analysis of the effectiveness of applying the LCA method in the environmental assessment of buildings on a large group of 73 cases from 13 countries. A similar research area was adopted by Sharma et al. [60], who also studied the performance of the LCA in assessing buildings located in different areas, but focused in particular on energy consumption by building types and greenhouse gas emissions. Rashid and Yusoff [55], Chau et al. [25] and Islam et al. [61] reviewed the LCA, Life Cycle Energy Analysis (LCEA) and Life-cycle cost analysis (LCCA) methods to distinguish building materials that have a significant impact on the environment. The problems with using the LCA method to compare the impact of individual buildings on the environment indicated by Anand and Amor [57] were analyzed by Soust-Verdaguer et al. [27], who identified possible simplifications for each study to develop LCA. A similar research area—verifications of the application nature of the LCA method for assessing the construction sector were carried out by Saynajoki et al. [26]. The applicative nature of LCA can be found in work by Vilches et al. [62], who investigated the impact on the environmental assessment of renovations and renovations of buildings carried out using the LCA method. Further possibilities of us-

ing LCA in Building Information Modeling (BIM) were investigated by: Lu et al. [63], Llatas et al. [64] and Potrc Obrecht et al. [65]. Lu et al. [63] performed a critical analysis of BIM integrated with LCA and life-cycle costing (LCC). Llatas et al. [64] focused on the possibility of integrating the Life Cycle Sustainability Assessment (LCSA) with the process of building design and BIM. Potrc Obrecht et al. [65] analyzed the advantages and disadvantages of various methods of the BIM integration process with LCA. The construction area is extensive, hence attempts to use the LCA method also for individual construction products. Yurong Zhang et al. [66] undertook a literature review on applying the LCA method in the concrete production process with the use of ore waste recycling. Concrete is the most widely used construction product. Its annual consumption is estimated at between 13 and 21 trillion tonnes [67]. Sustainable development requirements and the considerable production needs of concrete promote the use of waste materials in its production. The use of recycled aggregate concrete (RAC) is becoming more and more common, and the LCA method allows to compare the environmental impact of concrete production using the traditional natural aggregate concrete (NAC) and RAC methods [2,68,69]. Dong et al. [52] (p. 4), while reviewing the literature, indicated the need to compare the environmental performance of buildings. The existing criteria have been developed based on: (1) the level of greenhouse gas emissions, (2) stages of the life cycle of a building, (3) absolute or relative value, (4) analysis of the entire building or its elements, and (5) top-down or bottom-up approaches (Hollberg et al. [53]) (see Table 1).

To answer the research question—what emission levels should a building have throughout its life cycle, for different impact categories, respectively, Dong et al. [52] applied two research methods: (1) case study selection and (2) comparative analysis using CML 2001 [70] and IMPACT 2002+ [61]. As a result of the research, the factors influencing the environment of the building's life cycle (including three stages: (1) production, (2) use and (3) end-of-life) were identified and grouped by categories (Table 2).

Table 2. Description of the impact categories and the conversion factors.

Impact Category	Indicator	Unit	Referecne Method	Conversion Factors
CLIMATE CHANGE	Global warming potential for time horizon 100 years	kg CO ₂ eq	CML	Non Specified: 1 TRACI:1.012 IMPACT 2002+: 1.048 ReCiPe: 0.983
ENERGY DEPLETION	Abiotic depletion of fossil fuel related to the lower heating value	MJ	CML	Non specified: 1 TRACI: 12.672 IMPACT 2002+: 0.958 ReCiPe: 42.748
EUTROPHICATION	Eutrophication potential of emission of nutrients	kg PO ₄ eq	CML	Non specified: 1 TRACI: 0.471 IMPACT 2002+: 10.397 ReCiPe: 3.951
ACIDIFICATION	Acidification potential	kg SO ₂ eq	CML	Non specified: 1 TRACI: 1.061 IMPACT 2002+: 1.058 ReCiPe: 1.227

Table 2. Cont.

Impact Category	Indicator	Unit	Reference Method	Conversion Factors
OZONE DEPLETION	Ozone depletion potential of different gases	kg CFC-11 eq	CML	Non specified: 1 TRACI: 0.770 IMPACT 2002+: 1 ReCiPe: 0.159
PARTICULATE MATTER	Fine particulate matter equivalent for respiratory inorganics	kg PM _{2.5} eq	IMPACT 2002+	Non specified: 1 TRACI: 0.942 ReCiPe: 0.659
HUMAN TOXICITY	Human toxicity potential describing fate, exposure and effects of toxic substances	kg 1,4-DB eq	CML	Non specified: 1 TRACI: N.A. IMPACT 2002+: N.A. ReCiPe: N.A.

Note: N.A.—not available. Source: Dong, Y.; Ng, S.T.; Liu, P. A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review. *Building and Environment* **2021**, *204*, 108162, <https://doi.org/10.1016/j.buildenv.2021.108162>, [52] p. 6.

Dong et al. [52] indicated a correlation between the suggested categories, but two of them deserve special attention: climate change and energy depletion. Comparing types based on different units of measurement requires their prior normalization (Figure 2).

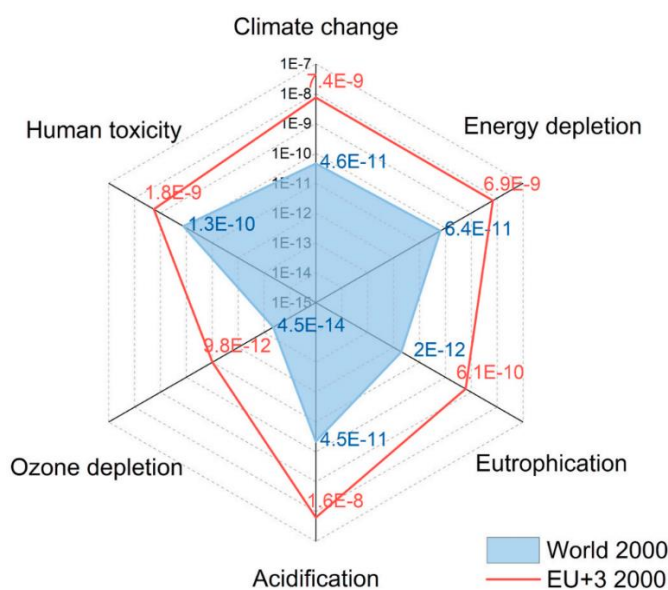


Figure 2. Normalized medians of impact categories for the entire life cycle of buildings (50-years' service life). Source: Dong, Y.; Ng, S.T.; Liu, P. A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review. *Building and Environment* **2021**, *204*, 108162, <https://doi.org/10.1016/j.buildenv.2021.108162>, [71] p. 12.

A literature review by Dong et al. [52] deserves special attention, as it touched upon the problems of comparing buildings using the LCA method, previously highlighted by Anand and Amor [57], or by Soust-Verdaguer et al. [27]. The conducted analysis of as many as 105 cases allowed to observe significant discrepancies for all the indicated impact categories. Dong et al. [52] reported comparative analysis of LCA results not always mentioned climate change, and depletion of energy sources are essential impact categories. In general, LCA is a method that allows to estimate the cumulative environmental and social effects associated with the production of a product or the provision of a service. [72,73]. An important element of the use of LCA in the implementation of sustainable development is the identification of key areas of the production process that have the most important impact on the environment [74]. Currently, a significant burden on LCA is access to information within the entire life cycle of a product, which is crucial for its effectiveness

and the ability to estimate its environmental impact [75,76]. The effectiveness of using LCA to assess the impact on the environment and its barriers can be analyzed on a wide level—systemic, organizational and the enterprise itself. The systemic barrier is the geographical complexity of supply chains and production processes, the use of outsourcing significantly reduces the possibility of obtaining data necessary to assess the impact of a manufactured product or service using the LCA method. On an organizational level, individual suppliers often do not keep the necessary production process data, and consumers still have a limited understanding of environmental issues. Barriers at the enterprise level result from limited financial resources or limited human resources [77]. In addition, the problem of the possibility of testing the impact on the environment with the dispersed organization of production processes also arises from the legal framework [78]. Taking into account the specificity of production processes, the LCA method must therefore be based on assumptions and simplifications, which is its significant limitation [79–82].

There are two LCA methodologies in the literature: retrospective and prospective. The retrospective LCA describes environmentally significant flows related to the life of the product and its subsystems. The goal of a prospective LCA is to describe how environmentally relevant flows will change in response to possible decisions [83,84]. Both retrospective and prospective LCA analyzes have methodological limitations that result from access to data and their standardization [81].

4. Life-Cycle Assessment Based on Blockchain Technology

The research question posed in this article regarding the possibility of supporting the use of blockchain technology in the LCA method requires illustrating its impact on the traditional structure of the LCA model [68] (Figure 3). It is worth recalling that blockchain technology allows: (1) to ensure traceability and transparency of the goal and scope definition, (2) at the inventory analysis level—by using the Internet of Things (IoT) concept, collecting and integrating data collected in real-time, and (3) at the level of impact assessment—create analytical forms [85] (Figure 4).

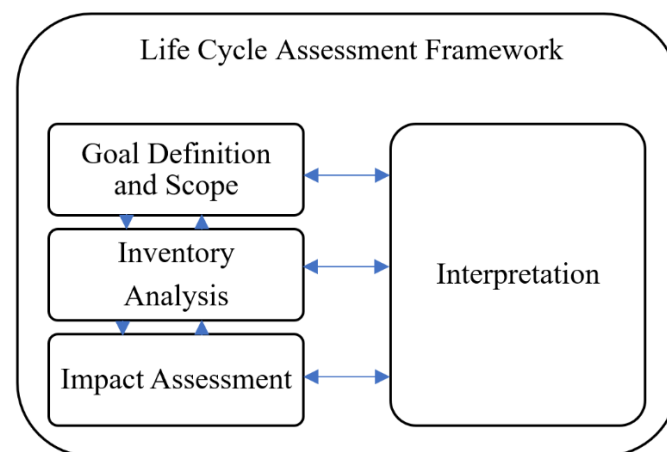


Figure 3. Life Cycle Assessment Framework. Source: ISO. Environmental management—Life Cycle Assessment—Principles and Framework. *International Organization for Standardization* 2011, 3, 20. <https://doi.org/10.1016/j.ecolind.2011.01.007> [68].

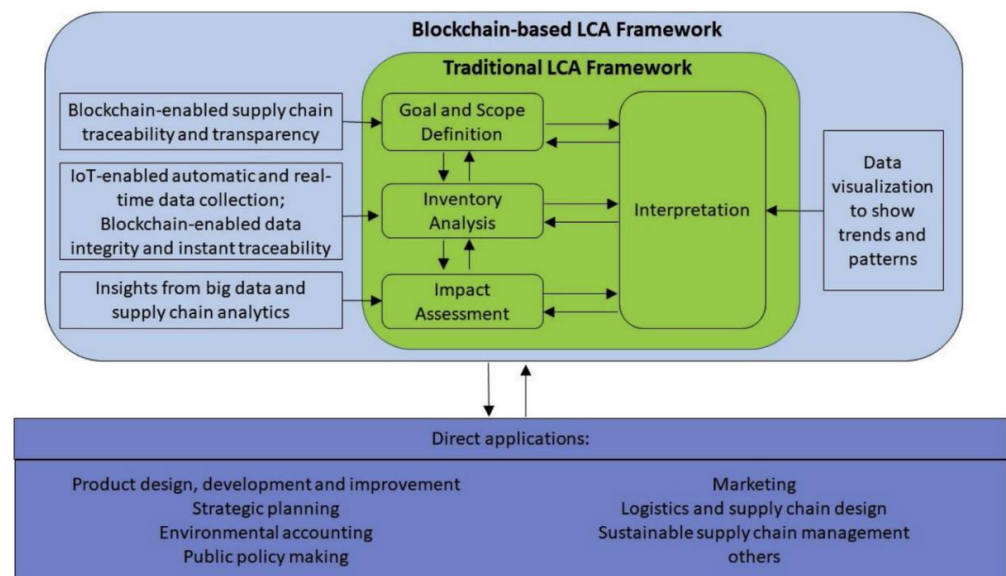


Figure 4. Blockchain-based LCA Framework. Source: Zhang, A. et al. Blockchain-based life cycle assessment: An implementation framework and system architecture, *Resources, Conservation and Recycling*. Volume 152, January 2020, <https://doi.org/10.1016/j.resconrec.2019.104512>, [85] p. 4.

The four phases (levels) of the LCA method defined by the ISO standard are supported by blockchain allowing operational excellence at all levels. The problem of the analysis and comparability of a large number of data in the LCA method, indicated in the literature on the subject, appears at its first stage. According to the assumption, LCA should comprehensively examine the product life cycle, from obtaining raw materials, production, use of the product, its reuse, maintenance, recycling, and finally its disposal [86]. The time constraints mentioned by the researchers, data availability, and financial resources will have the final impact on the effectiveness of the LCA method [33]. Genovese et al. [87] indicate that the use of blockchain solves other LCA problems of quantitative data regarding material and energy consumption in production processes, which are diagnosed by Rebitzer et al. [88] on the second level. The use of blockchain and IoT technologies at the third level of the LCA—impact assessment allows for much more detailed analyzes. The IoT technology is supported by sensors and devices that generate a huge amount of data in real-time, which allows for a more precise determination of the potential influence of the discussed impact categories, e.g., energy consumption or climate change [71,89,90]. The use of blockchain in the three phases of the LCA method allows, in the last, fourth—interpretative stage, to properly assess the product life cycle based only on relevant data. Moreover, the mentioned collection of vast amounts of data in real-time significantly increases the possibilities and functionalities of the LCA method: better use of production resources [91,92], more efficient management of supply chains [93], reduction of production time [94], and consequently gaining a competitive advantage by enterprises [95].

The aforementioned advantage of blockchain technology—the ability to collect, process and analyze huge amounts of data in real time, which is the basic element of correct LCA estimation, may also be its greatest threat. Sameri et al. indicate the problem of access to data and competitive advantage. Blockchain technology would facilitate the sharing of information through LCA activities, and some stakeholders, e.g., the company's management or shareholders, may consider access to such information as an element of a competitive advantage, and therefore may consequently consider it confidential [96]. Hence, restricting access to information would significantly hamper LCA implementations with blockchain technology [97]. Another factor determining the possibility of using blockchain in LCA is the participation of many stakeholders involved in the process of collecting and processing data (e.g., an extensive production process involving several

entities), which is a significant challenge in the organization and management of this process [98,99].

Teh et al. studied the possibilities of using blockchain in the implementation of LCA as part of a sustainable development policy and strategy on the example of the materials industry, in particular, they examined how the use of blockchain in LCA can meet the challenges of integrity, traceability and data transparency [100]. The implementation of new technologies allows to achieve new possibilities, but a frequent problem in life cycle assessment is still low availability of life cycle inventory (LCI) [101–103]. Certainly, new technologies such as blockchain, IoT will allow to collect, combine and analyze large amounts of data, which will revolutionize the data inventory process necessary for the effective use of LCA [104]. Still, a significant limitation is the relatively low dissemination of these technologies. A successful example of blockchain implementation is the Dutch dairy sector, where the data inventory process (LCI) lasted up to several months, and the use of the application programming interface (API) made it possible to shorten this period to zero and ensure almost immediate access to this data, and thus increased the effectiveness of the method LCA. [105]. The energy sector is another example where blockchain technology successfully increases the economic and environmental efficiency of the energy production process. The benefits of using blockchain include, among others: reducing transaction costs by eliminating or reducing the need for intermediaries in operating the system, increasing the consistency of energy standards, collecting data on energy production and CO₂ emissions in real time [106].

5. Conclusions

Supporting the LCA method with blockchain technology is undoubtedly the right direction of increasing the effectiveness and eliminating the limitations of this method for calculating the environmental impact assessment. In addition, the ability to process data in real-time thanks to the use of IoT allows for broader use of LCA in every branch of the economy or industry. In this article, the authors focus on using the LCA method in sectors with the most significant impact on the environment. Still, a more common measurement of individual elements of production chains in all economic areas is advisable. It will allow for the collection of data and their ongoing analysis, optimization of production processes, reduction of production costs, rational management of natural resources, and ultimately increasing competitiveness. The use of blockchain technology will allow for a more precise determination of the impact of the economy or a particular product on the environment and has a measurable economic feature. This trend is not only in line with the EU strategy and priorities [1], but is also of interest to Corporate Social Responsibility (CSR) [107,108]. The literature review indicates the need for further research in the field of analysis of potential areas of use of LCA based on blockchain technology [45,49,50,100,109–111].

However, the authors point to the existence of a research gap in the study of the effectiveness of collecting and analyzing data using blockchain technology when conducting LCA. Conducting further research in this direction will allow us to better verify the usefulness of blockchain in eliminating the current burdens of the LCA method.

Author Contributions: Conceptualization, R.K. and P.M.; Methodology, R.K., P.M., G.T.M. and J.W.; Project administration, P.M. and J.W.; Resources, P.M.; Supervision, R.K.; Writing—original draft, R.K., P.M. and G.T.M.; Writing—review & editing, R.K., P.M., G.T.M. and J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was not supported by any external source. The authors take all responsibility to prepare and conduct research.

Data Availability Statement: The graphs presented in the publication were taken from publicly available scientific articles. Detailed information about the source of the publication is attached to each graph.

Conflicts of Interest: The authors declare no conflict of interest.

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