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ORIGINAL ARTICLE

Digitalizing Circular Economy through Blockchains: The Blockchain Circular Economy Index

Davide Basile[a], Idiano D'Adamo[b], Valerio Goretti[a] and Paolo Rosa[c]

[a]Department of Computer Science, Sapienza University of Rome, Rome, Italy; [b]Department of Computer, Control and Management Engineering, Sapienza University of, Rome, Italy; [c]Department of Management, Economics and Industrial Engineering, Milano, Italy

ABSTRACT

The integration of circular economy (CE) models into everyday contexts generates huge amount of data involved in goods tracking and tokenization procedures. The sector of blockchain platforms is extremely varied, and the choice of the proper technology is not easy. It is important that the selection is conducted consistently with respect to the CE models. With this study, we present a performance index named Blockchain Circular Economy Index (BCEI). BCEI, obtained through Multicriteria Decision Analysis and Analytic Hierarchy Process, aims to measure the suitability of blockchain platforms to the needs highlighted by a CE scenario. The present study is contextualized by comparing six blockchain platforms, for each of which, the related BCEI is calculated. The results of the analysis show that transaction fee and energy consumption are the two most critical parameters. In addition, the results show the lack of a leading blockchain technology in CE models. Thus, there is a market space that can be exploited given the growing interest in digital and sustainable issues.

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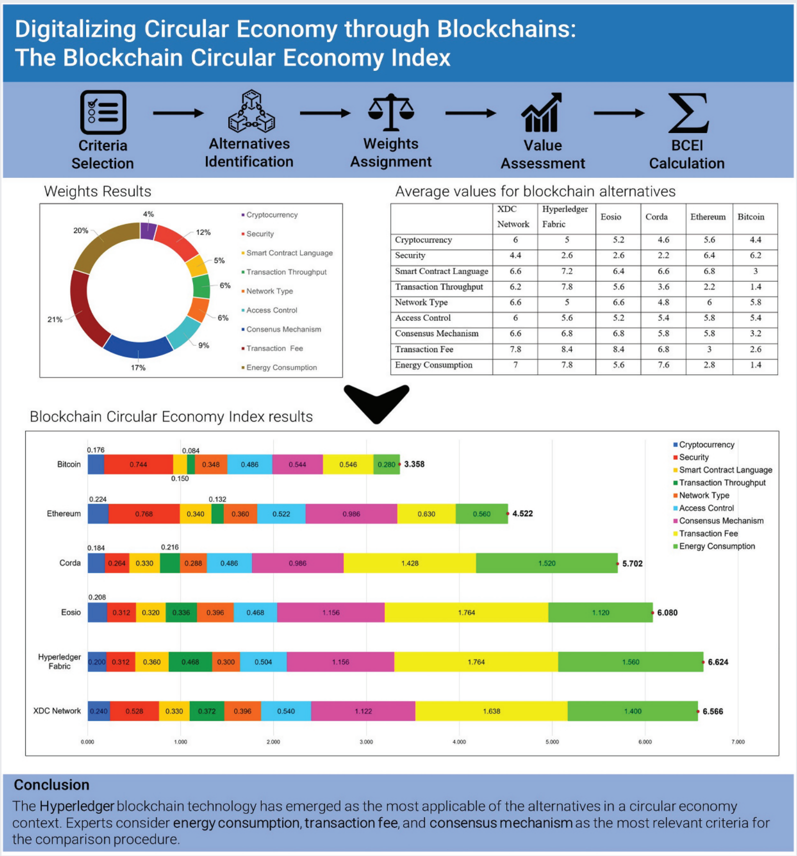

1. Introduction

In recent years, the shortage of raw materials has highlighted the need for the adoption of sustainable policies, aimed to reduce waste and maximize reuse. Circular Economy (CE) provides an economic model involving the generation of value from already used products, by

CONTACT Idiano D'Adamo idiano.dadamo@uniroma1.it Department of Computer, Control and Management Engineering, Sapienza University of, Rome, Italy

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reducing waste and consumption of raw materials [1–3]. The European Commission adopted legislative proposals to increase recycling initiatives and move toward a zero-waste future. End-of-waste strategies and social change should be viewed as enablers of circular practices in their contexts of reference [4] as the technological dimension must be optimized with the other dimensions of sustainability [5].

Several CE realities have emerged, and numerous organizations are investing into more sustainable models [6,7]. IT systems have proved to be essential in the transition process, supporting innovation and competitive advantage [8] and allowing the identification of alternative businesses [9]. CE involves the acquisition and management of large amounts of data. The integration of the proper technology becomes a crucial aspect of the design process. Big data, internet of things, artificial intelligence, and data storage play an important role in this regard [10]. Among emerging technologies, Blockchain platforms highly fit the CE needs [11,12] and generally find greater attention within the literature [13,14]. However, the relationship between CE and blockchain needs further studies to evaluate best practices and maximize benefits [15–17]. Blockchain can be viewed as a social technology or a tool for coordination in the context of the circular economy. Blockchain facilitates the connection and coordination of multiple distributed databases [18] that are updated simultaneously and accessible to all parties. In addition, the circular economy benefits from implementing a decentralized principle of value creation and circulation, rather than value creation and value appropriation [19].

To this aim, the present work wants to propose a new reference index (called Blockchain Circular Economy Index – BCEI) supporting decision makers during the selection of a proper blockchain within a CE scenario. BCEI allows the comparison of existing blockchain technologies based on their compatibility with CE principles and, starting from it, the identification of the most suitable platform to adopt. Hence, the main objective of the paper is to demonstrate the validity of BCEI through its direct application on existing blockchain platforms. To this aim, six of the most famous blockchain platforms are compared in terms of BCEI values and the obtained results will be discussed accordingly. This is needed to understand which of the compared alternatives performs best from a sustainability perspective, to identify which criteria most influence these results, and to highlight numerically some critical issues that might affect the reference context.

The paper is structured as follows. Section 2 presents a literature review on blockchains. Section 3 describes the adopted methodology. Section 4 presents the results of the analysis. Section 5 concludes the paper with some remarkable elements and future trends.

2. Literature review

2.1. Circular economy and blockchains

The CE and blockchain technology are two of the most emerging topics [20, 21], yet the need to identify connection points emerges overwhelmingly [22]. An infrastructure in which information is shared and transparent is essential to enable the proper flow of resources and materials throughout the product life cycle [23]. Blockchain provides such an information infrastructure [17]. The main areas of interest have been circular supply chains to identify the most suitable design and production of circular products by changing both material flow cycles and the development of new business models [24]. In this context, blockchain supports the tracking of resource and material flows in supply chains and consumption stages, while it does not support sustainable design or maximization of product use [25].

Blockchain technology reduces transaction costs in a circular model by improving performance and communication along the supply chain, as previously highlighted. In addition, blockchain ensures the protection of human rights and improves social accountability [15] by supporting coordination between different distributed databases [18] and in general the wider stakeholder network to ensure a cyclical lifecycle by enabling automation where needed [19, 26]. However, this change also requires costs for the business to bear to implement this new technology moving toward the digital economy [27]. There are still many challenges to be overcome as while the benefits in demonstration and testing phase are clear, there are infrastructure problems in the industrial implementation phase, including interoperability shortcomings, technology security, and stability issues. The risk that is seen is that of rising overhead costs not balanced by financial benefits in the short term, which makes such projects unsuitable for small businesses [28].

2.2. Existing indexes on blockchain in circular economy

Blockchains are Distributed Ledger Technologies (DLT) adopted to record and track transactions [15]. Then, transactions are stored into encrypted blocks and validated through a consensus mechanism. Blockchains are based on a decentralized shared database providing transparency and immutability of transaction records. Originally implemented by the well-known cryptocurrency Bitcoin [29], they evolved to offer a trust-free platform for execution of arbitrary business logic through many alternative blockchain platforms (e.g. Ethereum [30] and Hyperledger Fabric [31]). Given the continuous evolution of blockchain technologies, they are becoming fundamental in several sectors [32]. Decentralization, encryption, and distribution make blockchains highly robust and secure data structures for storing confidential information [33]. Blockchains are widely used in supply chain scenarios, improving the transparency and traceability of the production process [34–37]. To avoid counterfeiting and falsification during the production flow, blockchains enable the exchange of digital tokens associated to physical objects, allowing end users to analyze the history of products, from its origin to the purchase [38, 39].

The needs for tokenization and transparency are manifested also in CE scenarios. The collection, recycling, and reuse of materials should be tracked and quantified. Blockchains allow to store the processing materials undergo. Users and machines are allowed to access data anytime and observe the recycling process [40]. The world of blockchains is extremely varied and platforms differ from each other in numerous aspects. Blockchains can be public, private, or hybrid [41, 42]. They can use different cryptocurrencies, consensus mechanisms, or fees, and each of them determines different costs, consumption, and performances [43]. Analyzing the scenario from a managerial perspective, the appropriate choice of the specific technology can be complicated in a sustainable context [5]. This work covers a gap in the literature, as there are no methodologies that currently identify an index to measure performance from a CE perspective.

3. Methods

3.1. The context of analysis

The industrial context is moving toward an integration of the social component of the life cycle in the evaluation of products [44], following circular models [1] but without neglecting aspects peculiar to digitization [45], simulation models [46] and gender equality [47]. Internet of Things development is being examined at the European level as the digital aspect facilitates processes and stakeholder conveniences, but the impact on the environment and health must always be monitored [48]. Section 2 shows that there is a scope to be evaluated related to the relationship between CE and blockchain technology, but this is possible if there is circularity of resources.

In this regard, it is necessary to have an overview of the whole field, and the focus of this study is on the European sphere. Through the contribution of recycled materials to raw materials demand index, Eurostat measures the quantity of reinjected material into the European countries' economy. According to Eurostat [49], the first European country in 2021 is Netherlands, with a circularity rate equal to 33.7%, followed by Belgium (20.5%), France (19.8%), and Italy (18.4%). Furthermore, a comparison among European countries proposes a circularity performance in which the situation of Europe is significantly different based on a Multicriteria decision analysis (MCDA) [50]. This method is also used to evaluate the blockchain in terms of risk [51]. In addition, MCDA is supported by the Analytic Hierarchy Process (AHP) when it is necessary to provide quantitative assessments based on expert background to select the most relevant criteria [52].

3.2. Multicriteria decision analysis

MCDA is an analytical methodology used to compare different conflictual alternatives and to perform choices [48]. The effectiveness of this benchmarking tool for decision-making processes is shown by several studies, in which the usage scenarios are numerous and very different from each other [53, 54].

In this sub-section, we broaden discussion on the research methodologies and the related data sources, in order to clarify the steps that characterize the conducted work. MCDA is introduced to define an index, called BCEI, which makes the blockchain platform comparison possible. The reliability of this methodology is profoundly influenced by the criteria selection, weights assignment, and value assessment processes. The best alternative can be identified through some criteria. If the alternatives to be compared are already known, one proceeds to evaluate which criteria are most suitable to use. If, on the other hand, there is a topic that needs to be analyzed (relationship between blockchain and CE) and a literature review is conducted to identify the most recurring criteria, the next step is to evaluate the fields of application of these criteria (i.e. the alternatives). This can be achieved by assigning weights to criteria (which are valid for all alternatives) and values to criteria (which are alternative-specific).

Finally, the weights and values can be aggregated to have a summary indicator that evaluates the alternatives. In the following sub-sections, we will go into detail about each of the referenced procedures. According to the work of Öztürk and Yildizbaşi [55], MCDA is useful to identify the most relevant barriers to the integration of blockchains into supply chain management. Differently, some authors ideated a multicriteria-based approach to support decision-making for the design of blockchain applications [56]. This research proposes a method to identify and analyze multiple criteria and compare different blockchain platforms, defining an adaptability index. The goal of the BCEI is to highlight the alternatives that are most likely to be used in a CE project. The process by which

Figure 1. Main phases of the BCEI calculation.

we have pursued the target is composed of several steps – Figure 1.

Initially, a set of criteria is selected. Next, all the blockchain alternatives are identified and a numerical weight is assigned to each criterion. Afterward, attribute values corresponding to the blockchain alternatives are determined for all the criteria. Finally, the performance index is calculated for each alternative, according to the assigned weights and values. The final outputs are used to carry out a comparison of the blockchain platforms. However, more research is needed to evaluate best practices and maximize benefits in the relationship between CE and blockchain [15–17].

3.2.1. *Criteria selection process*

3.2.1.1. The selection procedure. The success of MCDA crucially depends on the way in which the comparison criteria are selected. The underlying goal is that criteria provide different points of view on the alternatives, with respect to the problem we are trying to solve. At this stage, this work aims to identify the main blockchain's descriptive features and to use them as distinctive elements, regarding the theme of the CE. A selection process that considers only subjective and narrow views can provide a biased viewpoint. Blockchains are extremely composed technologies, and their classification criteria are multiple.

According to this, this research proposes a literature-based approach thanks to which the initial set of criteria is identified. The first phase of the approach involves the search for publications dealing with the classification of blockchain technologies. To this end, the research team employed the search engine for academic publications, Google Scholar. The results considered are associated with the keywords "blockchain taxonomy." The documents resulting from the search operation have been reviewed and filtered by prioritizing those with (i) a significant number of descriptive criteria for blockchain technologies; (ii) a higher relevance in terms of pertinence to the searched keywords. At the end of the process, five documents have been identified [55, 57–60] that led to a total of 36 classification criteria.

3.2.1.2. Identification of critical criteria. Once the criteria have been defined, they have been filtered according to their occurrence in the five documents, as shown in Table A1 [56–60]. A criterion is selected if it appears in at least half of the works analyzed (three out of five). In a context where the number of criteria is at most 10, a classical AHP is used; however, if more criteria are identified, the local-global priority method of AHP should be used [52].

The critical criteria which passed the selection process are Security, Network Type, Access Control, Consensus Mechanism, Transaction Fee, Energy Consumption, Cryptocurrency, Smart Contract Language, and Transaction Throughput.

3.2.2. *Alternatives identification*

MCDA provides a metric-based approach to analyze different alternatives and carry out a comparison. The main goals of this work are the design of a rigorous analysis methodology and the demonstration of its implementation by evaluating famous blockchain platforms, from a circular perspective. Different blockchains have been selected to produce a set of alternatives. At the end of the process, six blockchains have been selected.

Bitcoin and Ethereum are popular public blockchain platforms, whose digital assets have reached considerable peaks. Corda and Hyperledger are private platforms widely used in industry. XDC Network is a hybrid blockchain, which combines the features of both private and public blockchains. Finally, Eos is a public blockchain platform that enables the development of app with high scalability.

3.2.3. *Weights assignment through Analytic Hierarchy Process Analysis*

3.2.3.1. The identification of experts. MCDA methodology involves weighting processes thanks to which criteria relevance is defined. The proposed weight assignment process is based on the AHP method. It is an eigenvalue model that derives a priority scale through experts' evaluations [61]. Also, this method is widely used to evaluate circularity performance [62].

The identification of the experts committee represents a key role for the success of the whole procedure. The selection process was guided by the need for contextual knowledge. According to this, a list of authors with some keywords was selected on Scopus, and only researchers with at least 10 years of experience were chosen. The keywords considered were blockchain technologies, CE, and project management. An invitation e-mail was sent, specifying the purpose and mode of the study, indicating that only the first 10 accessions would be chosen. Ten academics from five different countries (Italy, Austria, Brazil, England, and Germany) have been selected, and the analysis was conducted between April and May 2022 – Table A2.

3.2.3.2. Analytic Hierarchy Process. Experts were asked to compile a questionnaire and to elaborate a list of priorities through criteria pairwise comparisons. For each expert, a comparison matrix has been produced, in which a single cell expresses the numerical result of the confrontation between two criteria according to the Saaty 9-points scale [61]. Specifically, scores ranged from 1 to 9, where: 1 = equal preference; 2 = equal to moderate preference; 3 = moderate preference; 4 = moderate to strong preference; 5 = strong preference; 6 = strong to very strong preference; 7 = very strong preference; 8 = very to extremely strong preference; and 9 = extremely strong preference.

All the cells of the matrix are normalized, and for each criterion the considered weight is the average of the scores related to the comparison with the other criteria of the table. The thrust worthiness of the matrices is monitored through the calculation of the consistency ratio. In all the cases, experts have provided comparison matrix whose consistency ratio is equal or below 0.10, a score which ensures the reliability of the evaluations [61]. As a result of the questionnaire session, ten weight vectors (one for expert) were produced. Finally, the criteria weights considered for the MCDA are collected in the mean vector of the 10 expert vectors.

3.2.4. Values assignment

In order to successfully complete the MCDA process, values should be assigned to each blockchain for all the nine criteria. Features related to each criterion are retrieved from official blockchain channels, websites, white papers, and articles. Many of the selected criteria involve qualitative values, which does not enable an objective evaluation. In order to correlate each feature to a numerical value, another questionnaire session was necessary.

Different expert evaluations are used to turn qualitative features into numerical values. Experts were contacted through LinkedIn and selected according to the technical knowledge of blockchain platforms and their experience (at least 10 years). In this case, a number of five experts were chosen considering their more technical profile. In accordance with what was done before, several invitations were sent out specifying the purpose and mode of the study. It was, moreover, specified that only the first five accessions would be chosen. The analysis was conducted between April and May 2022 – Table A3. Each expert was asked to rate each criteria feature of all the alternatives, with a range of values from 1 (the lowest preference) to 10 (the highest preference). Once all the experts have assigned their scores, a value matrix has been generated, in which the two dimensions are blockchain alternatives and criteria. Each cell of the matrix expresses the mean value among all the experts' assignments for the blockchain alternative, regarding the respective criteria.

3.2.5. Performance Index calculation

Once weighted the criteria and assigned the values, it has been possible to calculate the performance index for all the alternatives. The following formula represents the calculation of the Blockchain Circular Economy Index (BCEI):

$$BCEI_{(Block\ chain\ Alternative)} = \sum_{i=1}^{N} RV_{(i)} \times CV_{(Block\ chain\ Alternative)(i)}$$

The two main components for the final calculation are the row vector (RV) and column vector (CV), obtained through the weighting process and the values assignment. N represents the total number of criteria, while i is related to the specific criteria index. The column vector expresses for each blockchain-criteria pair a numerical value. The row vector contains the weight of each criterion. The final score for a blockchain alternative is given by the summation of each criteria value, to each of which the related criteria weight is applied.

4. Results

After the values and weights aggregation, all the components for the BCEI calculation are available. The main goal of this section is to show and analyze the results coming from experts' consultations and finally compare the blockchain platforms through the BCEI of each alternative.

4.1. Assessment of weights

4.1.1. The aggregation of weights

The first expert consultation session produced ten 9 × 9 matrices, in which normalized pairwise are aggregated. At the end of the process, the opinion of each expert is represented as a numeric value between 0 and 1, which expresses the percentage of relevance of the criteria. For example, expert ten's matrix assigns 0.28 to Energy Consumption, 0.20 to Transaction Fee, 0.21 to Consensus Mechanism, 0.10 to Access Control, 0.05 to Network Type, 0.05 to Transaction Throughput, 0.04 to Smart Contract Language, 0.06 to Security and 0.02 to Cryptocurrency.

The opinion of each expert is equally weighted for the final average calculation. The results are proposed in graphical representation in Figures 2-3.

4.1.2. The analysis of weights

Transaction Fee is considered the most relevant criteria, with a mean value of 21%. It refers to the cost

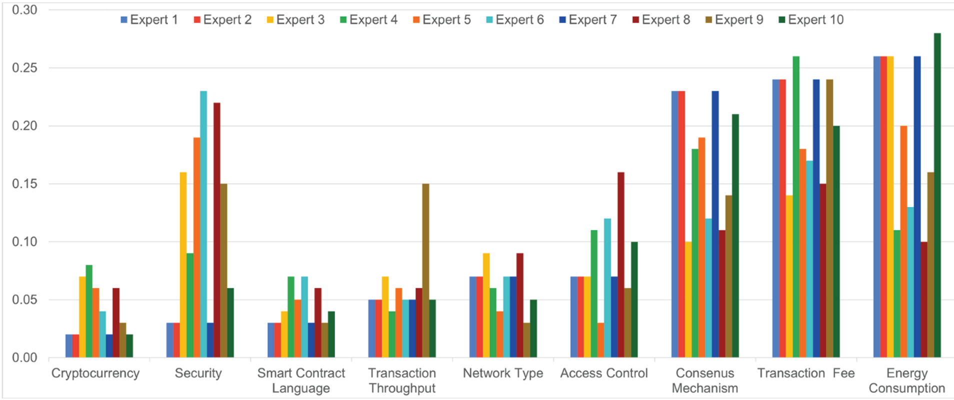

Figure 2. Weights results for blockchain features.

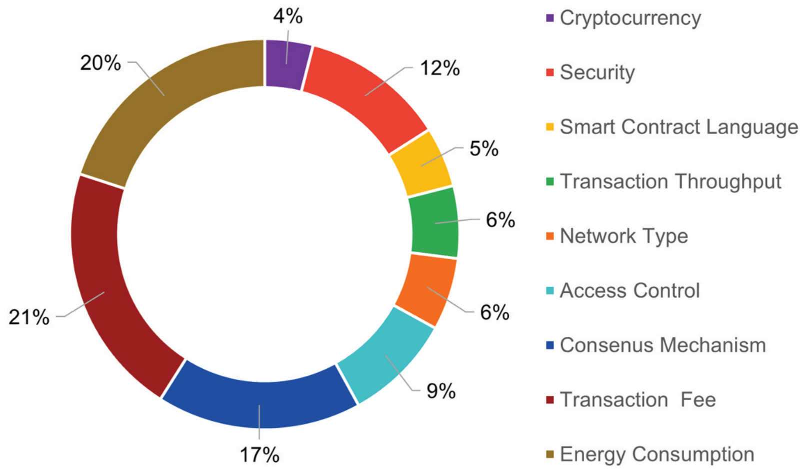

Figure 3. Weights distribution.

that is charged to users/organizations to add new data to the blockchain. The onerousness of the amount varies according to a multiplicity of factors related to the specific blockchain environment [63]. In a CE perspective, a blockchain-based project can result in an extremely high number of transactions per second. The majority of the already proposed CE models are expected to affect citizen behavior in their daily lives. Traceability and tokenization procedures, typical of a CE project, involve the generation of considerable volumes of data, to be frequently recorded. This explains the experts' opinion, which considers the cost of recording a crucial factor for the platform selection.

Energy Consumption is the second most relevant criterion, with a mean weight of 20%. The criteria relate to the amount of energy consumed to maintain the blockchain infrastructure. In many cases, blockchain has proved to be particularly costly technologies in terms of consumed energy [64, 65]. Unsurprisingly, experts have strongly weighted this feature. The CE model bases its principle on reuse and waste reduction [66], and a blockchain platform selection process should guarantee consistency with this regard.

Consensus Mechanisms are blockchain algorithms which ensure data validity and consistency, in a distributed environment [67]. This feature may affect different aspects of a CE project, like efficiency, costs, and consumption. The experts strongly evaluated this feature, assigning relevance percentages between 10% and 23%. Its average value (17%) is lower only than the first two mentioned criteria.

Following the relevance order, a lower value is assigned to the Security criteria (12%). Blockchain technologies spread data across multiple independent nodes. In a CE perspective, sensible data of organizations (i.e. production details) or individuals (i.e. purchasing information) are exposed. However, the vast majority of blockchain platforms already guarantee a high degree of confidentiality, integrability, and availability for the stored information, through cryptographic methodologies. According to experts, the Security criteria is an important factor to consider in the selection process, but not distinctive enough to make the final decision.

More technical blockchain features such as Access Control, Transaction Throughput, Network Type, and

Smart Contract Language achieve lower weights. Their average relevance percentages are, respectively, 9%, 6%, 6%, and 5%. These results are surprising, since experts in the technical field were consulted too. The lowest relevance is assigned to Cryptocurrency, whose mean value is 4%. The monetary value of blockchains' digital assets strongly suffers from rapid market fluctuations. Tokenization processes for CE models should not be excessively related to this issue. According to experts' opinion, these criteria must not be overly considered for the final decision.

4.2. Assessment of values

4.2.1. The aggregation of weights

In the second round of interviews, five blockchain experts have been surveyed in order to assign values to the six blockchain alternatives. The selected platforms are open-source blockchains, and each criteria information is publicly available. However, most of the identified criteria (Cryptocurrency, Security, Smart Contract Language, Network Type, Access Control, and Consensus Mechanism) expect qualitative information that do not enable an objective evaluation. For all the collected characteristics, experts' know-how has provided quantitative values, translating each feature to a value between 1 and 10. For example, considering the Smart Contract Language criteria, expert five assigns 3 to XDC Network, 3 to Hyperledger, 2 to Corda, 3 to Ethereum, and 2 to Bitcoin.

After the opinion collection, each of them is equally considered for the average value calculation. Due to space constraints, this work is not able to show all 270 values. This study presents the average values coming from experts' assessments in Table 1. The analysis of the values' distribution underlines uniform judgments, with peaks for values 7 and 3. Precisely, the following percentage distribution was determined: 1 = 7.8%, 2 = 10.0%, 3 = 14.1%, 4 = 8.1%, 5 = 6.7%, 6 = 10.7%, 7 = 17.4%, 8 = 10.0%, 9 = 7.8%, 10 = 7.4%.

4.2.2. The analysis of weights

Regarding Energy Consumption, experts show their preference toward Hyperledger Fabric (average value 7.8). The platform is known for its low consumption, with average by $1.0*10^{-}$[8] TWh. Hyperledger Fabric achieved the best average score also for Transaction Fee (average value 8.4), Consensus Mechanism (average value 6.8), and Transaction Throughput (average value 7.8). In the field of Smart Contract Languages, assignments highlight a higher preference for the JavaScript/Java/Go combination rather than Solidity. The less valued language is Bitcoin Script.

Another important aspect emerged from the analysis concerns the technology network type. Experts tend to devalue private technologies against hybrid and public network types. Unsurprisingly, technologies with lower Transaction Fee and Transaction Throughput are more valuable than platforms with higher costs and latencies. Regarding Consensus Mechanisms, the proposed algorithms achieve similar assessments with average values between 6.8 and 5.8, except the Proof of Work. The latter has received low ratings, with an average value of 3.2. Generally, interviews revealed strong skepticism toward the Bitcoin platform, which achieves the lowest average value for the 67% of criteria. The analysis shows that the latest technologies, XDC Network and EOSIO, are positively considered. XDC Network gets the best average score for the 33.3% of criteria, with values higher than 6 in 66.67% of cases. EOSIO determines similar performances, with positive values (6 or higher) in 64.09% of assignments.

4.3. BCEI for blockchains

4.3.1. Baseline scenario

The BCEI has been obtained through the product of two variables: the row vector and the column vector. The BCEI is determined for each proposed alternative. Its numerical value expresses the suitability of the blockchain platform with respect to the appropriateness to a CE project. The BCEI enables an objective comparison of the proposed alternatives. The results are represented in Figure 4.

The analysis of the results has underlined clear trends that are shared by various assessments. The crucial factors that affect the index most are Consensus Mechanism, Energy Consumption, and Transaction Fee. These elements are the features that a CE implementation should consider most. Differently, blockchain technical features are individually considered less relevant. This aspect highlights a degree of

Table 1. Average values for blockchain alternatives.

	XDC Network	Hyperledger Fabric	Eosio	Corda	Ethereum	Bitcoin
Cryptocurrency	6	5	5.2	4.6	5.6	4.4
Security	4.4	2.6	2.6	2.2	6.4	6.2
Smart Contract Language	6.6	7.2	6.4	6.6	6.8	3
Transaction Throughput	6.2	7.8	5.6	3.6	2.2	1.4
Network Type	6.6	5	6.6	4.8	6	5.8
Access Control	6	5.6	5.2	5.4	5.8	5.4
Consensus Mechanism	6.6	6.8	6.8	5.8	5.8	3.2
Transaction Fee	7.8	8.4	8.4	6.8	3	2.6
Energy Consumption	7	7.8	5.6	7.6	2.8	1.4

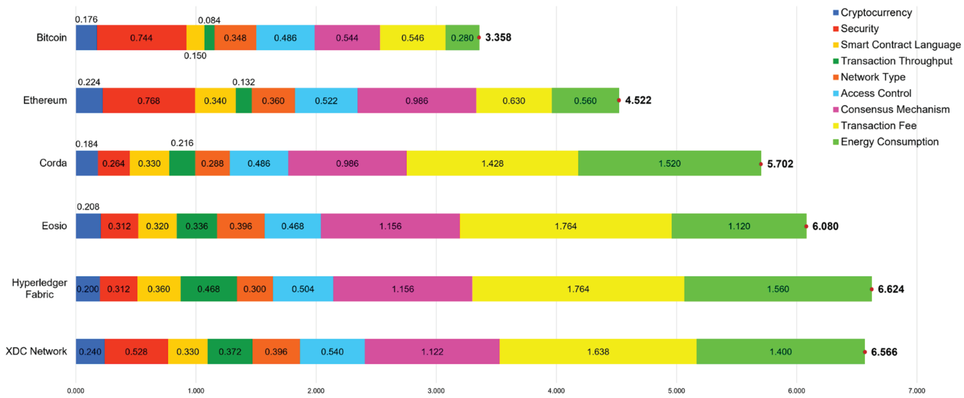

Figure 4. BCEI results.

adaptability of CE principles to such fields. The results show high incompatibility between CE and Bitcoin (BCEI = 3.358). Despite the monetary value of its native cryptocurrency, the platform raises many doubts about its sustainability. Its consensus mechanism used for block validation, the Proof of Work, is a very onerous algorithm. It is estimated that Bitcoin consumes annually 1.47 * 10^5 GWh, a value higher than the consumption of the whole of Sweden in 2020 Cambridge Bitcoin Electricity Consumption Index. Cambridge Bitcoin Electricity Consumption Index. The platform determines also a considerable average transaction fee, about 2 USD/tx, and reduced versatility in smart contract writing. Similar results are achieved by Ethereum (BCEI = 4.522), also considered insufficient from a CE perspective. The platform is slightly better seen than the previous one, in Consensus Mechanism, recently mutated from the Proof of Work to the more sustainable Proof of Sale, and Transaction Fee. Another similar aspect that the two platforms' shares is the Security evaluation, which is the only feature with higher values than the other alternatives. The large-scale use of both technologies resulted in greater reliability during the value assessment process.

The analysis of the results shows that none of the other alternatives distinctly prevails over the others. Their BCEI range is grouped between 5.7 and 6.6. The blockchain platform which gets the best result is Hyperledger Fabric (BCEI = 6.624). The platform is well known for its low consumption. Moreover, the absence of transaction fees and the higher transaction throughput (10,000 transactions per second) make Hyperledger Fabric a good candidate for the implementation of a CE project. A very similar result is achieved by XDC Network, with BCEI = 6.566. The platform is a relatively new technology that combines features of both public and private blockchains. Its consensus mechanism, called Delegated Proof of Stake, is a more efficient version of the classical Proof of Stake, involving a voting mechanism for the validator's election. The same protocol is implemented by EOSIO, which achieves a BCEI = 6.080. The Corda alternative (BCEI = 5.702) turns out to be slightly penalized by its adaptive transaction fee system that varies the cost according to the total number of transactions of the network.

4.3.2. Alternative scenario

In order to present a more robust result analysis, an additional index calculation has been carried out, in which all the criteria have the same weights (equal to 1/9). These alternative results are compared with the weighted BCEI scores. The equally weighted results are XDC Network = 6.86, Hyperledger Fabric = 6.24, EOSIO = 5.82, Corda = 5.27, Ethereum = 4.93, and Bitcoin = 3.71. The only rating difference involves the first position, which is occupied by XDC Network, rather than Hyperledger Fabric.

The consistency of the equally weighted calculation with the BCEI results shows that the proposed assessment goes beyond the CE perspective, and the evaluations can be generally extended to more contexts.

5. Discussion

5.1. Theoretical implications

The theoretical point of view proposes a methodological approach that enables a quantitative comparison of the technologies. The considered evaluations embed several aspects of the blockchain selection, which are mathematically expressed through weights and values assigned to criteria. The criteria multiplicity highlights the multidimensionality of the issue, which needs an analysis based on several themes.

This approach can easily be transposed in other contexts, without the need to distort its foundation. One of the main goals of the work was to examine an evaluation methodology that is as objective as possible and to provide theoretical tools to compare blockchain technologies in several scenarios. The proper application of MCDA and AHP is crucial in this regard.

In order to provide results that consider the issue in its entirety, experts' competencies should be properly mixed. In this case, it was essential to equally consider the technical view, related to the blockchain area, as much as the managerial and economic ones. Experts' reliability has been measured through their scientific impact in the field of blockchain technologies and circular economy. This paper provides assessments to consider whether blockchain technology is currently suitable for circular economy contexts and identifies managerial and policy implications.

5.2. Managerial & practical implications

The practical perspective of the study regards the analysis of the BCEI results. The application of the BCEI is potentially interesting for both private and public initiatives. Numerous local government agencies and corporate businesses are undertaking sustainable economic models. Blockchain technologies can improve the management of CE projects. However, the world of blockchains is extremely composed and the BCEI can be used as a guideline for the selection process.

The BCEI measures the platform performances considering both technical and sustainability features. However, transaction fee and energy consumption represent highly relevant factors for the evaluation process. The study considers six of the most popular blockchain platforms. Excepting Bitcoin and Ethereum, for which BCEIs underline high incompatibility with circular economy, the results for the other alternatives are decent but not exciting. A slight advantage is achieved by Hyperledger Fabric. Moreover, BCEI results determine another managerial consideration. The similarity of the obtained results highlights the lack of an industry leading technology in the CE sector. The presence of industry entry space and the growing demand determine good chance of success for investments in blockchain technologies, specializing in the management of CE processes.

5.3. Limitations and future directions

The results of this analysis refer to a generic CE context and this is a limitation of the work. However, this step is necessary to then extend this model to individual scenarios where CE models are applied. This work does not provide the whole picture of the market, but just a fragment with the most famous technologies. Future analysis will involve the extension of the present study, by applying the BCEI methodology to a wider selection of blockchain alternatives. In addition, other expert figures may be involved, increasing the number of criteria considered (through the local-global priority approach).

5.4. Policy implications

This work has provided quantitative assessments that are essential for policymakers to make the most appropriate choices. The European context sees a large amount of money allocated to sustainability and digitization projects. Clearly, common spaces can be triggered, but so can divergences, and some of the work has demonstrated this.

The first policy conclusion is to encourage the implementation of pilot models within the industrial context in order to monitor the relative economic benefits. Economic support on the cost of investment could make it possible to reduce economic risks. However, the measures to be applied cannot be the same for the entire industrial sector and obviously also for different circular contexts, which are characterized by different profitability conditions depending on the materials recovered. The idea is to enhance the excellence of local areas, which can foster local development models whose benefits can spill over to the national level with a view to greater global competitiveness.

However, the second policy direction is to foster sustainability analyses on the entire life cycle of a product in order to properly direct the use of public resources and to evaluate through MCDA analysis the most suitable blockchain technologies. Indeed, this work has provided a new tool that is capable of selecting the best alternative. Digitization should be calibrated with a view to the proper use of natural resources.

6. Conclusions

This work cannot be compared in the literature as it is the first to propose an MCDA-based approach to compare blockchain technologies suitable for use in a CE context. In a scenario characterized as much by values as by weights in accordance with business data, objectivity is more meaningful and adherence to reality is greater.

However, when these data are not available, reference should be made to expert knowledge. The results of this study are valid for the proposed criteria and refer to the chosen panel of experts. Clearly, a change in either of these aspects could lead to different results. Nevertheless, the recorded values suggest two clear indications. The first concerns the indication of the technologies that perform best in terms of circularity but nevertheless not achieving satisfactory values. This determines the second consideration, which then emphasizes the low propensity for sustainability of the evaluated technologies.

Furthermore, analyzing the two criteria that have been given greater prominence, some corrective actions turn out to be possible: transaction fee should provide discounted packages for those who make great use of it in order to find a proper mix between processed data and resource use, while energy consumption can reduce its effect through renewable energy. Digital technologies make it possible to reduce physical travel, improve manufacturing processes, and dematerialize many activities. However, their use should be modulated on the effects needed in light of reflecting sustainability goals as well.

The study confirms the need for quantitative studies that monitor the impact of technology in the combination of digitization and sustainability. This perspective must consider the process over the entire life cycle and needs to identify a suitable blockchain technology for CE models.

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No potential conflict of interest was reported by the author(s).

Notes on contributors

Davide Basile is a PhD student at Sapienza University of Rome, Italy. He holds a BSc and a MSc in Computer Science from the same university. His research interests include distributed ledger technologies and process automation.

Idiano D'Adamo is an Associate Professor of Management Engineering at the Department of Computer, Control, and Management Engineering of Sapienza University of Rome, where he teaches Business Management, Economics of Technology and Management, Economics and Management of Energy Sources and Services. Idiano was among world's top 2% scientists for third consecutive year (2019-2021). He received the Master of Science in Management Engineering in 2008 and the Ph.D. in Electrical and Information Engineering in 2012. Both from the University of L'Aquila. He worked in the University of Sheffield, the National Research Council of Italy, Politecnico di Milano, University of L'Aquila and Unitelma Sapienza - University of Rome. In August 2015, he obtained the Elsevier Atlas. During its academic career, Idiano D'Adamo published 118 papers in the Scopus database, reaching an h-index of 41. He has participated in scientific research projects (Horizon 2020 "Star ProBio", Life "Force of the Future"). His current research interests are bioeconomy, circular economy, green energy, sustainability and waste management.

Valerio Goretti is a PhD student at Sapienza University of Rome, Italy. He holds a BSc and a MSc in Computer Science from the same university. His research interests include blockchains and distributed architectures.

Paolo Rosa is a Post-Doc researcher in the Manufacturing Group of Politecnico di Milano, Department of Management, Economics and Industrial Engineering. He got his MSc in Management Engineering from Politecnico di Milano in 2009. He spent three years working as research assistant at Politecnico di Milano and ITIA-CNR in lifecycle simulation, manufacturing business models and end-of-life management areas. Currently, he carries out his research at Politecnico di Milano, by focusing on Product Lifecycle Management and Circular Economy. He has been (and he is still) involved in industrial, regional and European research projects and he won an H2020 project in 2018 (www.fenix-project.eu). He has been (and he is still) involved as teaching assistant in the Industrial Technologies course of Politecnico di Milano. He is co-author of 27 papers published in international journals, 15 papers presented at international conferences and he is co-guest editor of a Special Issue in the MDPI Sustainability international journal. He was awarded for the best paper in August 2015 with the Elsevier Atlas Award.

ORCID

Idiano D'Adamo http://orcid.org/0000-0003-1861-8813
Paolo Rosa http://orcid.org/0000-0003-3957-707X

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APPENDIX

Table A1. The criteria selection process.

Criteria	[56]	[57]	[58]	[59]	[60]	Total occurrences
Network Type	x		x	x	x	4
Transparency	x					1
Centralization	x				x	2
Auditability	x					1
Transaction volume	x					1
Privacy	x					1
Security	x	x			x	3
Scalability	x					1
Transaction throughput	x	x		x		3
Block Time	x	x				2
Consensus mechanism	x	x	x	x	x	5
Smart contract language	x	x	x	x	x	5
Cryptocurrency	x	x	x		x	4
Transaction fee	x	x			x	3
Simplicity		x				1
Size of the community		x				1
Ease of use		x				1
Ease of learning		x				1
Level of support		x				1
Access control		x	x	x		3
Availability of training and learning material		x				1
Energy consumption	x	x		x		3
Reputation		x		x		2
History		x				1
Updates and release of version		x				1
Advanced features		x				1
Support for web apps and mobile development		x				1
Purpose			x			1
Layers				x		1
Presence of smart contract				x		1
Presence of virtual machine				x		1
Innovation				x		1
Blockchain platform maturity				x		1
Gossiping					x	1
Block Header Data Structure					x	1
Block Storage					x	1

Table A2. List of academic experts.

Number	Role	Country	Years of experience
1	Associate Professor	England	12
2	Associate Professor	Brazil	14
3	Full Professor	England	20
4	Full Professor	Austria	18
5	Associate Professor	Italy	13
6	Associate Professor	Austria	14
7	Associate Professor	Italy	15
8	Full Professor	Germany	18
9	Full Professor	Italy	21
10	Full Professor	Brazil	20

Table A3. List of industrial experts.

Number	Role	Country	Years of experience
1	Operations manager	India	12
2	Plant manager	China	14
3	IT manager	Italy	20
4	Plant manager	France	18
5	Operations manager	Spain	13