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A Smart Contract Architecture Framework for Successful Industrial Symbiosis Applications Using Blockchain Technology

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Abstract: Industrial Symbiosis (IS) involves a network of organizations that exchange energy, materials, and by-products to lower production costs, reduce environmental impact, and conserve natural resources. Despite over two decades of extensive research into IS, its benefits are well known, but implementation remains challenging. This paper proposes utilizing blockchain technology (BCT) to digitize IS, making it more secure and transparent. First, drivers and barriers of BCT implementation in IS are identified. A smart contract architecture framework using Hyperledger Fabric is then proposed using the constructed theoretical background and abductive method. Finally, the paper discusses how this framework supports the implementation of BCT in IS by addressing its drivers and attempting to overcome its barriers. It is a resource for those seeking a comprehensive grasp of the foundational elements necessary for constructing a successful IS blockchain design, which is adaptable to all types of IS network configurations.

Keywords: circular economy; industrial ecology; eco-industrial park; digital; distributed ledger technology; smart contract

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1. Introduction

The change from a linear economic model to a circular economic model is proving to be essential to enable not only a reduction in the consumption of resources, but also a reduction of the quantities of waste generated and sent to incinerators and landfills [1]. Industrial Symbiosis (IS) is one of the solutions used to move from a linear model to a circular model. It is a sub-concept of Industrial Ecology (IE), which is considered to be one of the founding disciplinary fields of the Circular Economy (CE) [2–4].

IS first captured the attention of the world through discussions outlined in reference [5], proposing that the waste of one organization can serve as a valuable resource for another. Subsequently, the IS discourse in the literary world has been centered on the pursuit of synergistic inter-firm partnerships centered around physical material and flow optimization, as discussed in references [6,7]. The Kalundborg Eco-industrial park in Denmark is a preeminent example of successful IS, widely recognized as one of the most successful applications of IS and frequently cited in the literature, as noted in reference [8–11]. Since its earliest documentation, extensive research has been conducted to assess the impact of IS on the environment, economy, and society, as well as to explore strategies for promoting the wider adoption of this practice and addressing its vulnerabilities [12].

Despite over two decades of active research into IS and a clear understanding of its economic and environmental benefits, the practical implementation of IS has proven to be a challenge, as noted in reference [13]. In fact, at present, only a mere 0.1% of the 26 million European Union enterprises are known to be actively engaged in this field, as reported in reference [14]. The limited adoption of IS can be attributed to the availability of abundant and inexpensive resources over the past two decades, as noted in reference [15]. However, in the face of scarce resources and increasing societal and institutional pressure, there is a pressing need to address the lingering obstacles to the widespread dissemination of IS [16].

Information Technologies (IT) seem to be promising to promote the development and implementation of the IS concept [17]. For example, Blockchain technology (BCT) may have significant potential to help IS organizations collaborate and exchange data. This technology could provide a robust and reliable information management infrastructure [18,19]. In particular, it could solve problems related to the lack of trust between organizations through its ability to ensure the immutability and traceability of data. In addition, through smart contracts, it can be useful to improve transparency, communication, awareness and security in IS networks [20].

In this article, a smart contract architecture framework based on Hyperledger fabric is proposed. Furthermore, we discuss how this framework facilitates drivers and overcomes barriers of BCT application to IS. As such, this paper presents two fundamental contributions: one theoretical and one practical. Theoretically, it offers an exhaustive examination of the various elements to be taken into account during the construction and implementation of a blockchain application. It outlines a smart contract framework based on Hyperledger fabric that seamlessly integrates both business and engineering perspectives and encompasses the essential components and dimensions necessary for establishing a thriving IS blockchain ecosystem. It serves as a useful reference for those seeking a comprehensive understanding of the building blocks required for a successful IS blockchain design.

This paper is organized as follows. In the second section, the different concepts related to this research study such as IS, BCT and smart contract are described. In the next sections, we explain the methodology and then address the drivers and barriers of BCT applied to IS. In Section 5, the framework based on Hyperledger fabric is proposed and we discuss how this framework facilitates drivers and overcomes barriers of BCT applications to IS and then, strategies to overcome the barriers are discussed. Finally, the discussion and conclusion are, respectively, drawn in Sections 6 and 7.

2. Theoretical Background

2.1. Industrial Symbiosis

IS presents industries with the opportunity to cooperate in a mutually beneficial manner through the exchange of physical resources such as materials, energy, water, and by-products. The success of IS is dependent on collaboration and the synergistic opportunities arising from geographical proximity [7]. By embracing IS, businesses can reap economic benefits, as well as contributing to environmental and societal improvements through enhanced resource efficiency, reduced waste generation, and decreased greenhouse gas emissions via the exchange of materials, energy and by-products between various processes and industries [21].

One of the most emblematic examples of IS is the Kalundborg Eco-industrial park in Denmark, which has established industrial exchanges and cooperation for over 50 years, involving 9 partners and 25 flow exchanges [8–11]. Since its inception, numerous instances of IS have been documented in the annals of history, showcasing a diverse range of participants, economic pursuits and organizational structures [12]. The United Kingdom leads in the number of reported cases, owing to the government's National Industrial Symbiosis Program, a voluntary initiative aimed at facilitating partnerships between companies to utilize waste as raw materials [22–24]. Throughout the world, IS has been the subject of numerous initiatives, from both developed and developing nations. In China, for example, the adoption of IS has been influenced by the constraints on carbon dioxide emissions and the implementation of plans and policies promoting CE practices [25]. The United States boasts a history of IS that dates back to the late 1970s in Barceloneta, Puerto Rico, where pharmaceutical companies fostered the development of IS through inter-company exchange [26]. Other notable cases of IS can be found in Australia, Japan, Morocco, and Thailand [12].

IS is marked by different types of synergistic exchanges, which can be grouped into three categories [27]: Substitution synergies replace one process's input flow with another process's output flow, such as exchanging by-products. Pooling synergies pool the supply or processing of similar flows between multiple industries using or producing them, such as sharing infrastructure and services. The third category, information sharing, is crucial for creating opportunities for IS and involves exchanging information between stakeholders.

The practices of IS possess distinct attributes, which may be classified into three groups [28]: (i) those that arise independently, through the initiative of an industrial player; (ii) those driven by a top-down approach, with government or industry leaders devising a strategy to spur symbiotic relationships within a given area; (iii) those facilitated by a mediatory public or private entity, fostering the growth of symbiotic networks.

2.2. Blockchain Technology

BCT, which is used for information storage and transfer, stands apart from conventional database systems, as it operates without a central authority [29]. Rather, it relies on a decentralized and secure ledger which is accessible and verifiable by all permitted users without the need for a middleman. The technology comprises a series of blocks, linked together by unique identifiers, which form a chain and preserve a comprehensive record of all transactions among users from the moment of inception [30].

For many years, BCT was a technology known only to a select few who understood its technical aspects. However, over time, BCT gained popularity due to its use in the creation of cryptocurrency, particularly Bitcoin, introduced in 2009 by Nakamoto [31]. Bitcoin has since become a popular investment tool and means of financial transaction, outpacing even the performance of traditional assets such as the S&P 500 or commodities such as oil [32]. This surge in popularity attracted the attention of numerous banking and IT organizations, sparking a search for additional applications of BCT [33].

The once unknown technology of BCT has emerged and gained notoriety for its financial applications, such as the creation of the cryptocurrency Bitcoin. Yet, its unique attributes have also garnered attention from beyond the finance world, inspiring its incorporation into various markets and industries for non-financial purposes. Today, BCT is hailed as an innovative tool with the potential to streamline supply chains and enhance insurance contracts [33,34] and which can be used in the energy sector [35], health [36] and CE [37] with, for instance, Plastic Bank and Recyclass. Plastic Bank harnesses the power of blockchain technology to incentivize ethical plastic recycling in communities along the coast that are particularly susceptible to environmental degradation. The collected plastic is transformed and reintegrated into the global supply chain as "social plastic," and its journey is tracked and validated through the use of the blockchain platform. Meanwhile, Recyclass represents a collaborative effort across various industries to improve the recyclability of plastic packaging, and to trace the paths of both plastic waste and recycled plastic within Europe, by utilizing the advantages of blockchain technology [38].

In the domain of BCT, three distinct categories have arisen: public BCT, private BCT, and consortium BCT [39,40]. Public BCT offers an open arena where individuals from various organizations can participate and view all records, taking part in the consensus process. In contrast, private BCT serves as a platform for exclusive data sharing and exchange among a selected group of individuals or organizations, with the mining process controlled by one organization or chosen individuals. Finally, a consortium BCT is a type of blockchain that is operated by a consortium of organizations, rather than being open to the public or being controlled by a single organization [41]. It is a type of private blockchain where a group of organizations come together to share a blockchain network and maintain a decentralized ledger, while still retaining control over who can participate in the network and access the data stored on it.

2.3. Smart Contract

The smart contract concept was proposed by Nick Szabo in 1994 [42]. As an important part of the BCT, a smart contract is a computer program consisting of a set of rules executed on the BCT [43]. This program of intricate design securely stores the directives and protocols for negotiating terms and actions between various entities. Its purpose is to automatically verify if contractual conditions have been fulfilled, triggering execution of transactions accordingly. Guided by logic, it operates within a network of actors who must reach a consensus on the outcome of its execution. Upon receiving a message, the contract executes its coded instructions, which may originate from a network participant or another contract, and updates its records in accordance with the regulations of its public or private network, so long as the contractual conditions are upheld [44,45].

The smart contract is an important part of BCT and has several characteristics that allow it to be traceable and irreversible. Some of these characteristics include the fact that smart contracts are machine-readable codes executed on BCT platform. They are part of an application program, are event driven and are self-contained once created, and there is no need to monitor them; finally, they are distributed [43]. The smart contract is implemented in various BCT platforms and the programming language used is Solidity. Ethereum is currently the largest smart contract platform in the world [46].

Generally speaking, the BCT-based smart contract offers a number of advantages for a wide range of potential applications [43]. These include speed and real-time updates, accuracy, lower execution risk, fewer intermediaries, lower cost, and the development of new business or operational aspects.

These advantages allow it to be used in various economic sectors ranging from insurance reimbursements to financial transactions, from business operations to the traceability of goods and the protection of intellectual property [47]. One of the main applications is the supply chain, in which it is used to track the origin and flow of products, detect counterfeit and fraudulent items, exchange information and automate transactions [48].

2.4. Integration of Industrial Symbiosis, Blockchain Technology and Smart Contracts

The application of BCT and smart contract to IS and, more broadly, to waste management, was also highlighted as a promising application [49,50]. For example, the smart contract can allow agreements to be made between two or several organizations on the type of information and transactions without the need for third-party interventions. The smart contract makes it possible to establish a cryptographic digital identity for the organizations that participate in the IS and ensures the integrity and authentication of the data. The smart contract is also based on a number of predefined rules that determine the level and authority of each organization to access, save, retrieve and evaluate the data. For example, a public authority that would like to assess the effectiveness of the IS each year to calibrate its subsidies for the following year could retrieve certain data via predefined rules [51].

3. Methodology

An integral part of problem solving is deduction and abduction. The deductive approach begins with a preconceived theory or general idea, from which a hypothesis is created and tested through application of the theory or law. The conclusions are then based on the results of the test. In other words, in deductive reasoning, conclusions are drawn from what is known [52]. In contrast, the inductive approach starts with real-life observations, collects data from these observations and then forms a hypothesis and theory to explain them [53]. Both of these methods have limitations. The deductive approach may lead to incorrect conclusions if the underlying theory or rules are flawed. The inductive approach has a limited scope and cannot be generalized to all observations.

As a form of logical inference, abductive reasoning was introduced by Charles Peirce and involves constructing a theory to explain a given observation. The simplest and most likely explanation is usually deemed to be the most likely one, according to abductive reasoning. It is sometimes described as the "inference about what would be the best explanation" [54]. This allows the researcher to find the best explanation for a surprising observation that cannot be explained by established theory or to use an alternative theory or framework for the existing phenomenon. A hypothesis is then formulated and tested based on this matched theoretical framework. As such, creating abductive theories allows researchers to develop original theories without relying on existing ones [55].

The theoretical background indicates that there is limited research on the relationship between blockchain technology and industrial symbiosis. As a result, the deductive approach is not appropriate for this project due to the lack of theoretical knowledge. The inductive approach is also not feasible, as it would require a large amount of empirical data to create a generalized theory on the application of blockchain technology to industrial symbiosis. This theory would only be valid under specific conditions and the use of blockchain in industrial symbiosis depends on various variables. Thus, the abductive approach will be utilized in this study. In organizational and management theory, it is advantageous to actively acknowledge the role of abductive reasoning [56]. This approach allows for the creation of the best possible explanation for a phenomenon based on the available information, even if it is not complete and assumptions may need to be made [57]. For any model construction, abductive reasoning is essential to explain phenomena based on the best fit guess, which may lead to hypotheses deriving from the model and being empirically tested [58].

Several articles were consulted in order to identify drivers and barriers of BCT implementation in IS, and since they were scarce, a thorough search was performed so nothing could be left out. To collect the existing literature, the first step was the choice of keywords related to the objective of this study. Among these keywords, two groups were defined, a first group of keywords like "Industrial symbiosis", "Urban industrial symbiosis" and "Eco-industrial park". Then, a second group of keywords was defined like "Blockchain technology", "Distributed ledger technology" and "Smart contract". Then, these two groups of keywords were combined to make the search of publications. These combinations were used to search for articles in databases like Web of Science and Scopus. In the initial stage of our search, the only limitation was the language of the articles—they had to be written in English. The gathered information underwent a screening process, with a careful examination of the titles, keywords, and abstracts, in order to select the most pertinent articles.

Even the articles in which IS was not the main focus of the study and where IS only appeared as an example were selected to obtain a large panel of articles. Then, a content analysis of these articles was conducted to gather and analyze information. This analysis allowed us to identify the drivers and barriers of BCT application to IS. Finally, a framework was proposed for the application of BCT to IS, using the constructed theoretical background and abductive method. The abductive method enhances comprehension of both theory and empirical phenomena by enabling the researcher to switch between the framework, data sources, and analysis [59] in order to evaluate how the framework will enable and surmount challenges in the implementation of BCT in IS.

4. Blockchain Technology Applied to Industrial Symbiosis: Drivers and Barriers

Blockchain technology is expected to play a central role in the future of smart cities and businesses by facilitating interoperability and collaboration between organizations while improving data management, security, and process management. Private and consortium BCT have emerged as suitable architecture concepts in business settings, where participation in the network is restricted to specific individuals or groups [60]. Each architecture, public BCT, private BCT and consortium BCT has advantages and disadvantages for IS applications, Table 1 below shows them. Based on this table, it seems that consortium BCT is the best choice for IS application. In the literature, some authors argue that formation of consortia drives the financial support necessary to realize the full potential of technology [37,61,62], as others use private architecture BCT [63,64], while others discuss the implication of using public architecture BCT [65].

Table 1. Advantages and disadvantages of blockchain technology architecture for industrial symbiosis application.

	Advantages for IS	Disadvantages for IS
Public architecture	Improves transparency and auditability of information	Any entity can join the network, access the data and use blockchain ledger Low efficiency No specific validation nodes
Private architecture	High efficiency Facilitates private sharing and exchange of data between a group of individuals (in a single organization) or between multiple organizations Unknown users cannot access the blockchain	The network tends towards centralization
Consortium architecture	High efficiency The consensus process is controlled by pre-authorized nodes Possible to limit the reading of the blockchain to specific participants It is decided by the consortium whether read or write permissions will be public or restricted to network participants.	Restricting consensus to a set of nodes does not guarantee immutability and irreversibility, as majority control of the consortium can lead to tampering with the blockchain.

Based on the advantages and disadvantages, drivers and barriers are identified with the help of extended literature. The literature on the relationships between BCT and IS was scarce until now, so it also included research concepts such as CE and supply chain, for instance, as the barriers and drivers are similar, depending on the circumstance. Therefore, the drivers and barriers are identified and characterized. First, the benefits of applying BCT in IS are presented, and then the barriers to the adoption of BCT in IS.

4.1. Drivers of Applying Blockchain Technology to Industrial Symbiosis

In this section, drivers have been identified and characterized in three types. First, we present the drivers related to organizational aspects; these ones might aid logistical and organizational issues experienced by the stakeholders of IS in their operations, for instance. The second type of driver is related to financial issues. Additionally, the third type of driver is technological and might provide something different when compared to another technology or with no technology.

Technological and organizational drivers might help organizations and administrative authorities in their operations. There are two approaches to stimulate IS [66]. The first (top-down) approach involves a distinct vision and broad strategies on both a national and regional scale, along with proactive support of IS interactions by local and regional actors in collaboration with key private organizations. In contrast, the alternate approach is one where IS remains notably absent from policy discussions, and growth is instead driven by private entities and industrial parks. In both approaches, BCT has a role to play in stimulating IS. In the first one, where public authorities are involved, it can simplify administrative procedures through smart and tamer-proof contracts. In the second approach, BCT facilitates the integration of new private partners and trust between stakeholders.

With the introduction of BCT, the potential to revitalize waste and uncover new value has arisen. Utilizing electronic sensors and tracking devices, the location and worth of waste can be recorded and made accessible through BCT ledgers, enabling organizations to connect and exchange their waste with ease [50]. With the prospect of an increase in IS networks in a territory that would create numerous interconnections, BCT could simplify administrative procedures through smart and tamper-proof contracts [49]. Then, the technological and financial driver type is about financial optimization of financing programs. Stakeholders such as administrative and financial authorities can use the information stored in BCT to assess the effectiveness of waste exchange programs. This can help better target funding and optimize IS programs and thus better manage public funding [67,68].

Finally, there are several technological drivers related to BCT adoption in IS. For instance, the exchange of information between organizations regarding wastes and co-products can be difficult. In addition, tracing information across complex networks can be a real challenge. BCT makes it possible to gain trust and security between the stakeholders, which can promote the sharing of data and thus make collaboration easier and more efficient [69,70]. It thus facilitates interactions such as networking and co-creation, which are essential to the establishment of synergies of substitution and pooling. Additionally, the sharing of data allowed by BCT through these platforms is an important element that can facilitate the search and identification of synergies of substitution and pooling.

In utilizing the potential of BCT, a new range of possibilities opens up for the exchange and management of waste. This technology can serve as a bridge for interconnecting disparate systems and provide real-time information to all involved parties [50]. The utilization of smart contracts on the BCT platform can further streamline the process by enabling automatic execution of waste exchanges. With this technology, a comprehensive record of waste exchanges, including the quantity, value, and quality, can be maintained and made available to all stakeholders in the network. This precise information can be used to optimize the functioning of IS by building specific inter-organization information systems [67,71]. In traditional information systems, data are often centralized and thus susceptible to manipulation or failure. Blockchain technology, however, dispenses with central authorities and provides a decentralized structure, thereby reducing the risk of system failure. With its cryptographic signature architecture, BCT further enhances the security and dependability of records [50].

BCT holds a unique advantage over conventional information systems in fostering the flow of information between stakeholders. This is due to its unparalleled level of transparency, verifiability, and immutability. The very nature of the BCT network, where a recorded transaction can only be altered with the consensus of the network, instills an unprecedented level of reliability in the information it provides [19,71] (Table 2).

Table 2. Drivers of applying blockchain technology to industrial symbiosis.

Type of Driver	Code and Driver Name	Description	References
Organizational	D1—Facilitate data collection	BCT can help to better structure the logistical chain between stakeholders through the introduction of instruments and devices that help standardize and formalize the functioning of IS.	[50]
	D2—Facilitate administrative procedures	BCT can simplify administrative procedures through smart and tamper-proof contracts	[49]
Financial	D3—Optimization of financing programs	BCT can guarantee the traceability of waste and co-products exchanged between the stakeholders of an IS, which can reassure the administrative authorities in the future of waste on their territory and help to evaluate the efficacy of IS programs	[67,68]

Table 2. *Cont.*

Type of Driver	Code and Driver Name	Description	References
Technological	D4—Traceability of information	BCT can facilitate the flow of information between the stakeholders of an IS at the scale of an eco-industrial park, a county or a province	[50,72]
	D5—Optimize the operation of IS	Most of the time, there is no information system in industrial symbioses. BCT could be a way to develop and facilitate the collection and storage of information and working with operational data. This could make it possible to better control and optimize the operation of IS	[50,67,71]
	D6—Improving security	BCT can guarantee a certain level of security in its operation, unlike a traditional database	[37,49]
	D7—Trust between stakeholders	BCT can foster trust and transparency between the actors involved in an IS	[19,50,68,71]

4.2. Barriers to the Adoption of Blockchain Technology in Industrial Symbiosis

It is possible to classify these barriers according to their type. There are barriers related to social and cultural, organizational, economic, technological, and political aspects (Table 3). The cultural and social barriers incorporate perception of technologies and change issues [73–75]. Indeed, the negative perception of technologies, and more particularly of new information and communication technologies, leads to mistrust and a lack of confidence. This might be explained by the use of BCT in currency-related markets such as bitcoin or its use in illegal markets. BCT can also be the subject of behavioral concern in the sense that, for cultural reasons, some people may not want to use this technology. For instance, BCT involves a new system and it means replacing the old system; thus, these changes might cause hesitation and resistance from stakeholders.

Table 3. Barriers to the adoption of blockchain technology in industrial symbiosis.

Type of Barrier	Code and Barrier Name	Description	References
Cultural and social	B1—Negative perception of technology	Lack of confidence or perception in one or more actors in new information and communication technologies	[74]
	B2—Resistance to change	The reluctance on the part of the actors involved in the IS to use the BCT	[73,75]
Organizational	B3—Lack of coordination and collaboration	Lack of coordination and collaboration among stakeholders to make the BCT works on a daily basis	[76]
	B4—Lack of expertise	Lack of management and technical knowledge within organizations to operate the BCT	[77,78]
Financial	B5—Financial constraints	The initial investment in the development of a BCT architecture and in the operating costs that this entails	[79–81]

Table 3. *Cont.*

Type of Barrier	Code and Barrier Name	Description	References
Technological	B6—Immaturity of technology	The immaturity of the BCT can be a barrier to its adoption in IS	[74]
	B7—Challenge to energy consumption	BCT is known to consume a lot of energy to operate	[74,80]
	B8—Lack of devices to run BCT	Lack of IT infrastructure to allow the operation of the BCT in industrial sites	[82,83]
Political and economic	B9—Lack of incentives	Lack of reward and incentive systems to promote BCT and IS by government, local authorities and professional organizations	[84]

Then, the organizational barriers include internal firm and inter-firms concerns [76–78]. The first one is related to a lack of coordination and collaboration between stakeholders that can constrain the use of blockchain. This can be explained by the lack of trust, which does not favor collaboration, and therefore the coordination of waste and by-product exchange activities. Trust is an important prerequisite because stakeholders have little or no cooperation mechanism [85]. For this reason, it is important to promote social interactions between the stakeholders of an IS network.

Additionally, such lack of coordination might occur because of different priorities and operational objectives amongst the organizations implied. Regarding internal organization operation, BCT can involve different skills to be able to function. The utilization of BCT necessitates the availability of technical expertise to continually sustain the software and its data, as well as the need for administrative personnel to fulfill any legal responsibilities that may arise from its usage.

The adoption of BCT technology in an IS project may be hindered by the financial limitations of stakeholders. While the use of BCT has shown the potential for cost savings and elimination of paper-based procedures in supply chain contexts, the limited number of such applications renders these benefits merely indicative and subjective [79]. The implementation of BCT may incur low one-time transaction and storage fees, yet its utilization in a smart contract scenario is estimated to be costlier than conventional infrastructure solutions.

The technological barrier category incorporates immaturity, sustainability and infrastructure issues. BCT is still immature, which can create significant technological challenges such as scalability, usability and interoperability. For example, for interoperability, the BCT must be able to connect with the other digital tools of stakeholders [74]. Another major concern is related to sustainability issues because BCT is energy consuming [74,80]. The high computing power required for large "proof-of-work" consensus systems consumes several hundred megawatts of power. In a decentralized network such as BCT, the demand for computational power and resources necessary to secure the integrity of its records and entries, through duplication, leads to greater consumption of energy. Thus, this heightened energy expenditure results in an increase in carbon emissions. BCT requires certain infrastructure and equipment to run, such as information technology for all players such as the internet, Global Position Sensors (GPS), Internet of Things (IoT) and RFID technology. Some industrial sites are not yet equipped and this may slow down the establishment of the BCT on these sites [82,83].

The last category of barrier is related to political and economic issues. The lack of regulatory framework is also a barrier to the implementation of BCT. In the case of a planned IS approach—in other words, a top-down approach—public authorities play an important role in the implementation of IS. Thus, the lack of a regulatory framework to promote the use of BCT is a barrier to its implementation. This regulatory framework should facilitate, coordinate and encourage action through public–private partnerships and the use of digital technologies such as BCT. In addition to regulatory and financial support, public authorities could provide advisory support to organizations, particularly the local and regional authorities that know the field and the players well [84].

5. A Path to Facilitate Drivers and Overcome Barriers

5.1. A Smart Contract Architecture Framework

Some studies have made the connection between BCT and IS [18,19,51,68,86–88] and they have not investigated this relationship in more depth when BCT presents a real opportunity for IS. Indeed, BCT could be useful in different situations and promote the maintenance of IS [49]. For example, BCT could be useful from the perspective of a large deployment of IS in a territory requiring more precise monitoring of the resources exchanged and preservation of confidentiality. Additionally, in the case of a large deployment of IS that would create many and complex interconnections between value chains, BCT could simplify administrative procedures through smart and tamper-proof contracts.

In addition, data management in an IS business model is generally very little thought out. However, synergies can give confidential indications such as the quantity or quality of wastes and information on the level of activity of industrial sites, such as the production. The BCT could, in principle, provide an adequate response to the traceability via cryptography of the exchanges of materials between industrial sites. Likewise, BCT would be adapted for resources with a certain value and processed by several intermediaries, even more so in organized networks of industrial synergies for which traceability will become more and more complex. BCT could, in particular, certify the origin of a resource in the event of an incident that it could have created. The registry operation allows excellent traceability of the exchange of assets or transferred resources in the case of IS. This traceability would follow all types of assets throughout their life cycle, taking into account the intermediaries of synergies. This particularity would be a strong point for indirect synergies and the study of it. BCT could also, in principle, monitor the conditions of a contract (management of interdependencies) set up between two users of a platform. This system would simplify the conclusion of transactions.

Our study shows the emergence of blockchain consortiums in certain industries, as they offer advantages and are better suited to overcome barriers listed in Table 3, particularly barrier 3. These consortiums strive to bring together companies with similar goals in regard to blockchain and to promote blockchain-based business models and standards in these industries. As the authors of [37] mention, the CE objectives can further encourage consortium members to collaborate on a blockchain platform. With the aid of the data provided by BCT, stakeholders may gauge the success of waste exchange initiatives. Transactions of waste may be chronicled on BCT ledgers, yielding insights into the frequency of such exchanges within the network, as well as the value and caliber of such exchanges. This information can be obtained by integrating Enterprise resource planning (ERP) systems with BCT. Partners and stakeholders can form an integrated platform, which provides data that cannot be altered or altered via fraud, as well as audit trails for transactions that occur within the extended ERP network [89]. The decentralized architecture of BCT allows for great security around the data structure. Indeed, the principle leads to the fact that the data are not stored in a single server, but with some of the users. This then requires hacking a large number of the users at the same time to reach and decrypt the data.

Smart contracts are a key feature of Hyperledger Fabric and provide several advantages over conventional information systems for IS applications. Smart contracts are highly customizable and can be designed to meet the specific needs of different organizations. This makes them a more flexible solution when compared to conventional information systems, which often require significant customization to meet the needs of different organizations. Smart contracts can facilitate waste exchanges by automatically executing exchanges based on different factors inherent to the waste [50]. Additionally, the application of smart contract to IS may require trusted third parties to provide information on assets and manually update transactions. Often, this means that a third party must step in to certify the rules, terms and performance of the contracts that are signed, a role that is usually played by a coordinating or supervising agent [90,91].

As highlighted in [92], it is crucial to justify the use of blockchain and select the appropriate type based on a company or service's requirements. Figure 1 shows a visual representation of a smart contract formalization through Hyperledger Fabric between an industrial unit and two eco-industrial parks, in eight steps. Hyperledger Fabric stands as a cornerstone of open-source innovation. Developed by the Linux Foundation, it offers a distributed ledger infrastructure and a wealth of tools to aid businesses in utilizing blockchain technology [93]. This corporate platform is designed to enable the implementation of blockchain solutions and to provide access to a range of smart contract engines, client libraries, graphical interfaces, and sample applications [94]. Though Hyperledger Fabric is but one example of this technology, its versatility and proven track record make it a valuable asset in the world of IS configurations.

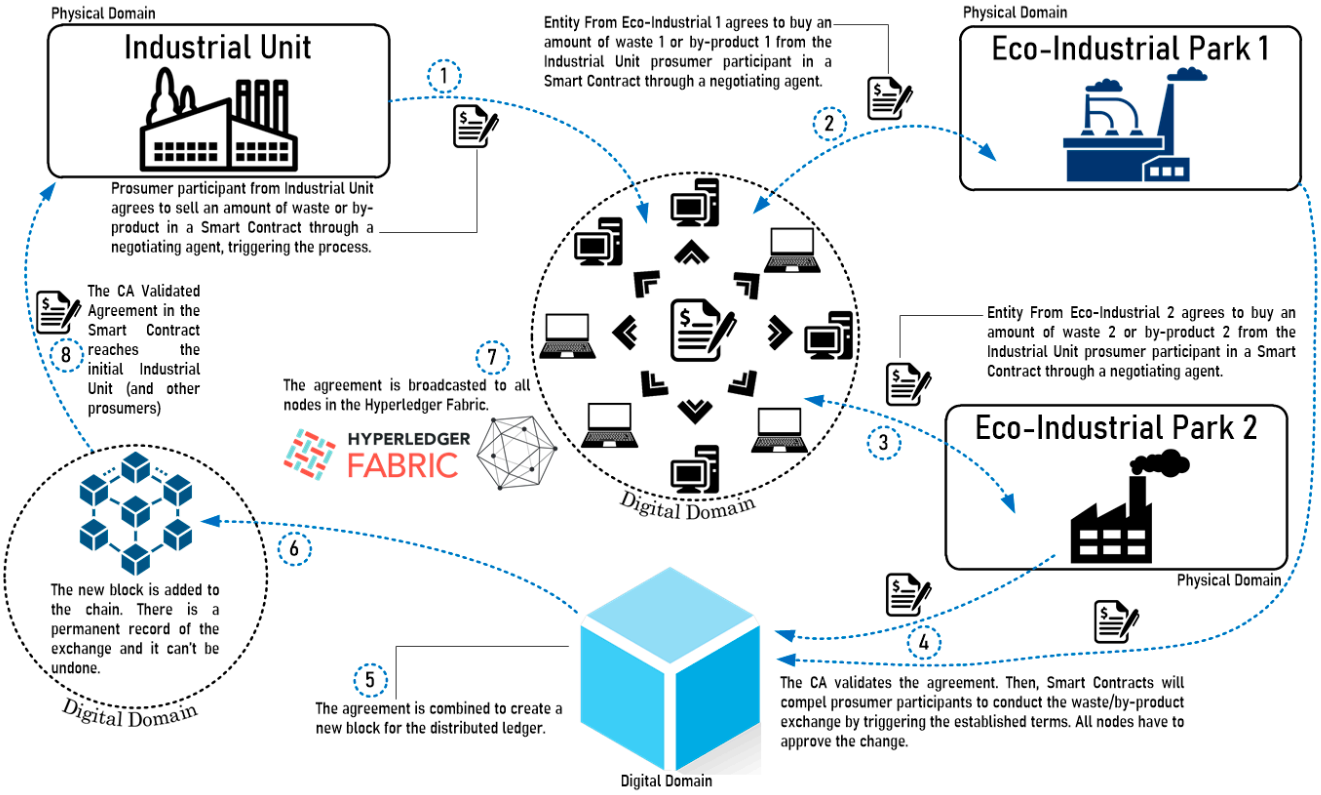

Figure 1. A visual representation of a smart contract formalization through Hyperledger Fabric between an industrial unit and two eco-industrial parks.

From an operational standpoint, ledger updates are achieved through a straightforward process, and are depicted in Figure 2. An industrial entity located within an Eco-Industrial Park initiates an application by submitting a transaction to the blockchain network. The means by which an application engages with a blockchain network involves utilizing the Fabric SDK [95]. Upon successful validation and commitment, the application is notified of the transaction's success [96]. This process involves a consensus mechanism in which the various components of the blockchain network collaborate to guarantee that each proposed ledger update is legitimate and executed in a predetermined and consistent sequence [97].

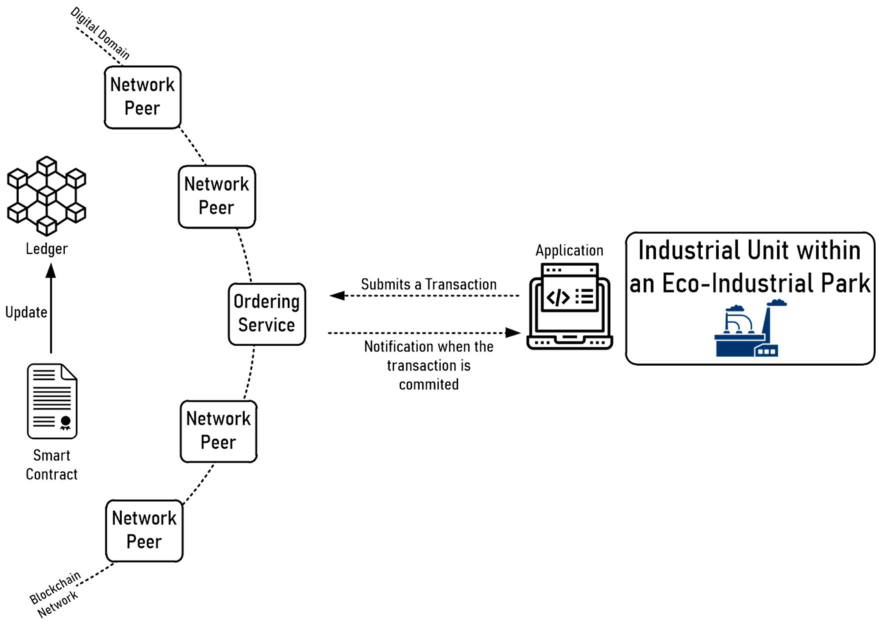

Figure 2. Visualization of ledger updates of an industrial entity located within an Eco-Industrial Park.

5.2. Strategies to Overcome the Barriers

Section 4 has characterized different types of barriers of BCT adoption to IS. These barriers cannot be overcome in the same way, so it is necessary to think about different strategies capable of tackling them, or at least reducing them. Here, we propose to list and describe these strategies with regard to each type of barrier.

The first category of barrier involves cultural and social issues [84]. Resistance to change, slow decision making and implementation processes can hinder the adoption of BCT in IS networks. Organizations may not be ready to change their culture, for example, changing their business model. In order to reduce this type of barrier, it seems judicious to carry out workshops, working group discussions and other actions likely to provide organizations with information on the potential of BCT in IS networks. Additionally, carrying out tests before concrete implementation can also be a way of reassuring these actors to provide them with proof of the added value of this technology. The involvement of authorities and local political bodies on this subject is a way of facilitating the engagement of all stakeholders around a common project.

The second category of barrier Involves organizational aspects and human skills [44]. Integrating BCT in organizations, and more particularly in IS networks, requires the will to integrate it into business processes, which implies the motivation to provide financial and human resources to implement it. Faced with the growing interest in blockchain resources and the lack of knowledge and technical expertise on BCT [98], there is an urgent need to train people in organizations and universities. In organizations, this involves training individuals who have been trained on the old system, which can lead to resistance and hesitation on the part of individuals and organizations [44]. As for universities, it seems important to train students in computer science courses in the development of BCT applications in different sectors of activity. Here, the proposed smart contract framework, through Hyperledger Fabric, is particularly useful, especially to overcome barrier B3. Even though, the blockchain ecosystem being considered is still in the design phase and aims to enhance the experience of current platform users by allowing seamless communication between buyers and sellers on different platforms.

The third category of barrier involves financial aspects. The implementation of BCT has a cost which can be broken down into several types of cost, and different strategies can be put in place to reduce this barrier. In their article, [99] broke down the different types of cost associated with implementing a blockchain-based smart contract in a waste application context with a municipality. They count five phases and estimate the cost for each of them: (i) consulting phase (10%), design phase (15 to 20%), development phase (50 to 60%), insurance (20 to 25%), maintenance and monitoring costs (15 to 25%). Some costs seem to be incompressible, but others can be mitigated. This is the case of development-related costs; for example, rather than developing a new platform, it may be considered to integrate an existing one to reduce costs. Additionally, for the costs related to maintenance and monitoring, rather than hiring a dedicated team, it seems more appropriate to hire the services of a specialized agency or a freelancer.

The fourth category is more technological in nature and involves issues related to the maturity of the technology or equipment enabling it to operate. The immaturity of blockchain makes users skeptical about the real-world applications of this technology and creates technical challenges including scalability, usability and interoperability. Faced with the immaturity of technology, IS networks should rely on external technical developers to advance the development of technology. BCT also needs time to develop and for organizations to prepare to equip themselves. Indeed, BCT needs technologies such as the IoT to track, trace and integrate waste and co-product information into IS networks [74].

The fifth and final barrier category involves political and incentive aspects [32]. The lack of government measures and incentives for the use of BCT in IS networks creates a real challenge for organizations and, more particularly, organizations to implement it. A lack of financial support and relevant measures reduces the potential for using BCT in IS networks. The evolution of regulations depends, above all, on raising consumer awareness towards a demand for more recyclable products and more product traceability. This can encourage policymakers to take different government initiatives and design local policies that promote the development of projects. Precursor organizations can also encourage policymakers to legislate towards laws encouraging other organizations in the same sector to do the same [65,100].

6. Discussion

The application of a blockchain-based network has been shown to offer significant advantages over traditional systems. Firstly, it facilitates rapid transactions and the seamless integration of new organizations into the network. Secondly, every transaction is recorded immutably in the blockchain, simplifying auditing processes. Finally, the blockchain architecture is highly scalable. While these benefits are substantial, there remains room for improvement in the design. For instance, the addition of a user-friendly front-end application could eliminate the need for users to interact with the Hyperledger Fabric's command-line interface. Furthermore, the transaction speed could be further optimized through the implementation of a built-in cryptocurrency, eliminating the need for manual payment processing. The field of IS seeks to reduce waste and make industries more sustainable. The adoption of BCT in IS systems holds great promise in realizing this vision on a global scale, enabling rapid and efficient implementation of these initiatives to create a more sustainable world.

Smart contracts allow IS actors to define the relationships and interactions of each of them within the system. In particular, this helps to define the governance and process rules within the IS such as actor certification and approval, the processes they are authorized to access and that are necessary for execution. Smart contracts also allow these actors to have their digital profile on the network and to display information on the description of their activity, the location as well as the state of the waste, its volume and its quality [50]. They can thus further facilitate waste exchanges by automatically executing exchanges based on different factors inherent to the waste. They can also have the advantage of saving time because the terms of the contract are already recorded. Additionally, in the case of a complex IS with many exchanges and intermediaries (carrier, processing center, etc.), the smart contract would facilitate the monitoring of exchanges, particularly for the administrative authorities, which would simplify the administrative procedures and therefore the time spent treating them. Finally, the smart contract is capable, from a financial point of view, of organizing the arrangements, ensuring that funds are available and sufficient, and that each actor can be paid in due time [44].

This study emphasizes the lack of scientific research in this area and calls for more research. The next step could be to work on the prioritization of barriers, which was not carried out in this study. This could help to clearly identify the efforts that are necessary to promote the implementation of BCT in IS projects. This would thus make it possible to guide decision makers in organizations, but also in public policy on the choices and decisions to be made to promote the development of this type of project. Besides, employing the proposed framework serves as an example of how it can be utilized in other enterprise blockchain applications. The need for more case studies and best practices is also important. We lack a successful implementation of BCT in an IS context to make this paper applicable and trigger other studies in this field. However, it should be noted that the implementation of BCT raises questions relating to data confidentiality. Because it is transparent to stakeholders, it is important to be aware that certain information may be shared and accessible within the BCT. This could, for some actors, be an obstacle to its use in this context.

7. Conclusions

Industrial Symbiosis (IS) is a circular business model in which separate organizations create a cooperative network to exchange materials, energy, water and/or by-products. While this concept has been the subject of research for more than two decades, its implementation remains a challenge due to the technological and socioeconomic barriers that its development process faces. More specifically, the lack of trust between organizations, of securing the data exchanged as well as the lack of infrastructure to support the business model and the management of data and transactions between the organizations involved, are among the key challenges in the IS development process. Information technologies seem to be promising to meet these challenges; in particular, Blockchain technology (BCT)-based smart contract may have significant potential to help IS organizations communicate, collaborate and exchange data into a secure, robust and reliable information management infrastructure.

Consequently, the aim of this paper was to generate a smart contract architecture framework based on Hyperledger fabric that brings together business and engineering perspectives through a balanced approach. It encompasses all of the vital components and dimensions required to establish a thriving IS blockchain ecosystem. As a result, it serves as a valuable resource for those seeking a comprehensive grasp of the foundational elements necessary to construct a successful IS blockchain design. The proposed blockchain ecosystem is still in its design phase, yet it has the potential to enhance the existing platform participants by fostering interoperability among buyers and sellers on disparate platforms. This application of the framework is very adaptable and serves as a demonstration of how it can be utilized for different IS configurations, offering a roadmap for their successful implementation, as it can be useful when implementing the blockchain IS network.

Until now, BCT has mainly been studied in other types of application such as the supply chain, but it seems to have real potential to be applied in circular business models, and IS is one of them. This field of research seems really promising to further deploy IS and promote its development in several regions of the world. This conceptual work calls for further research related to BCT and IS, eco-industrial parks and waste management more broadly. For example, there are still research questions to be addressed in terms of technological, economic, cultural and organizational feasibility in the context of IS. While this area of research is still in its infancy, there is a need to quickly test the ability of BCT to develop and foster IS networks in different contexts and countries. For this, it is necessary that public authorities and federations of BCT professionals fund research and facilitate the first tests in different application cases.

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