A Smart Contract Architecture Framework for Industrial Symbiosis

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Contributor: Aurélien Bruel, Radu Godina

Information Technologies (IT) seem to be promising to promote the development and implementation of the Industrial Symbiosis (IS) concept. 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. 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.

Keywords: circular economy ; industrial ecology ; eco-industrial park ; industry 4.0 ; digital ; blockchain

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][3][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][9][10][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].

2. 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][9][10][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][23][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.

3. 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.

4. 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].

5. 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].

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