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ORIGINAL PAPER

Blockchain and industrial symbiosis: a preliminary two-step framework to green circular supply chains

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Abstract
The strategic management of supply chains, by ensuring closed-loop manufacturing processes and a constant reduction of industrial waste, is an essential pillar of sustainability. This is the pattern behind the, so-called, circular supply chains. The effective adoption of this paradigm demands the supply chains actors to establish robust integration and relationships, so that waste and by-products of an industry or industrial process become the raw materials for others. This circular network is defined as industrial symbiosis. Starting from a background on this topic, this working paper explores the potential of blockchain as enabling technology of Industry 4.0 to disseminate industrial symbiosis practices within the modern industrial scenario. A preliminary two-step framework, i.e., conceptual and operative, is presented including insights and win–win synergies showing the potential of blockchain technology in supporting informative flows of industrial symbiosis. Preliminary field experiences are suggested, along with existing limitations and perspectives on future research.

Keywords Blockchain · Circular economy · Framework · Industrial symbiosis · Industry 4.0 · Waste valorization

Introduction

In recent years, two industrial paradigms are driving academic research and industry: Industry 4.0 (I4.0) and circular economy (CE). These debated topics are generally investigated as separated, but the combination yielded recent international discussions and interesting advancements. Emerging technologies are fostering unprecedent opportunities to address contemporary environmental challenges, supporting companies and final users to move toward CE (Rajput and Singh 2019; Rosa et al. 2020; Tseng et al. 2018; Ventura et al. 2023a). Industry 4.0 refers to digital and organizational changes in manufacturing systems to develop industrial competitiveness through the use of Internet technologies and smart objects. The Boston Consulting Group introduced in 2015 nine technology trends, i.e., big data and analytics, autonomous robots, additive manufacturing, simulation, augmented and virtual reality, horizontal and vertical system integration, Internet of Things (IoT), cloud computing and cybersecurity, that allow enabling flexibility, efficiency and high-quality industrial processes and goods (Lasi et al. 2014; Rüßmann et al. 2015; Bortolini et al. 2022b). Looking beyond the "take-make-dispose" paradigm, CE aims at designing out waste and pollution, keeping products and materials in use and regenerating natural systems. Instead of thinking to a finite lifetime, products and components are redesigned and rethought to facilitate disassembly and recycling after their first use. Finding sustainable solutions is essential for mitigating adverse human impacts on the environment, without, however, neglecting commercial and economic aspects. The closed materials flows and the use in multiple phases of raw materials and energy are at the core of CE definition (Ellen MacArthur Foundation 2024). Within this context, industrial symbiosis (IS) rises up as an emerging paradigm and option. IS has been defined as engaging distinct organizations in a system where materials, energy, water, services and by-products are exchanged among the participants of the network, reducing waste generation and environmental impacts. In this way, the waste and by-products of a company represent potential inputs for another business (Chertow 2000; Lombardi and Laybourn

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2012; Cutaia et al. 2015; Lawal et al. 2021; Neves et al. 2020). The term that specifically refers to energy exchanges among different production processes is known as "energy symbiosis" and represents a key part of IS. Energy symbiosis reduces fossil fuels demand and allows to recover waste energy from industrial processes (Afshari et al. 2020). Cooperation among traditionally separate companies reinforces sustainability in terms of environmental, economic and social benefits, also generating a collective benefit greater than the sum of individual contributions. Environmental sustainability of IS is related to the efficient use of raw materials and to the reduction of harmful emissions and waste. IS enhances the availability of critical resources, by ensuring a long-term resource security. Regarding economic benefits, the pursuing of IS allows to reduce costs of raw materials and disposal costs, by sharing resources and not disposing waste to landfills. Business and market opportunities are also boosted for the creation of partnerships among companies. Lastly, social advantages concern the creation of new green jobs, such as the resource manager, and the cultural shift toward sharing-economy and CE (Chertow 2007; Cutaia et al. 2015). However, the practical implementation of IS networks is still hindered by several factors, i.e., a mix of cultural, managerial, technological, legislative issues influencing the decision-making process of potential entrants. Further key aspects to face include the input–output matching for identifying industrial symbiosis opportunities, the establishing of business partnership agreements and the material and informative flows mapping within the network. I4.0 technologies, especially sensors, IoT and data analytics, represent innovative tools to improve the efficiency of the material flows by data (Ponis 2020; Järvenpää et al. 2021). Cutting-edge digital solutions for managing physical items, informative or energy flows, are fundamental to ensure a strong interconnection among the entities engaged in IS, to improve energy efficiency of transport and to reduce harmful impacts on natural resources (Kadłubek et al. 2022). Among the potential enabling I4.0 technologies, blockchain emerges as a viable solution to deal with complex decentralized informative systems characterized by multiple origins and destinations of the data flow. Operating as a distributed ledger, blockchain facilitates data sharing within a peer-to-peer (P2P) network. Each new transaction recorded on the system contributes to the creation of a block, linked to the previous ones, forming a chain. Blockchain technology became popular following the 2008 financial crisis and the subsequent development of crypto-currency and Bitcoin (Nakamoto 2008). While initially applied in the financial sector, blockchain inspired several sectors, including logistics and supply chain management (Queiroz et al. 2020; Lewis 2021). Blockchain offers several enhancements in terms of data traceability and transparency, addressing critical concerns for both IS and supply chain management. Implementing blockchain technology leads to decreased human errors, diminished information asymmetries, prevention of fraudulent activities, enhanced reliability and coordination across the value chain, as well as efficient tracking of products and associated information. Consequently, it fosters increased trust among consumers and suppliers (Bhalerao et al. 2019; Saberi et al. 2019). Platforms to share data based on blockchain technology are increasingly used in the energy sector, with P2P energy markets, especially for electricity trading for industries. These networks strengthen energy cooperation among the nodes and facilitate energy transactions trading (Dang et al. 2019; Pyakurel and Wright 2021). As stated in the summary report of Organisation for Economic Co-operation and Development (OECD) global blockchain policy forum (2019), CE and blockchain constitute a promising tandem for not only considering the origin of goods in supply chains, but also their end-of-life destination. Starting from this background, this working paper explores the potential of blockchain technology to support IS networks management. The aim is to present an updated review on IS and blockchain technology, serving as a initial point for setting a preliminary two-step framework, i.e., conceptual and operative. This includes insights on the win–win industrial synergies enhanced by blockchain technology, aiming at a consistent data flow throughout the supply chains. The framework is inspired by the existing experiences, taking their pros and overcoming their limitations, by enlarging the spectrum of analysis to a worldwide extension with a deep focus on Italy and European context up to early 2024. The reminder of this paper is organized as follows: Section "Materials and methods" reviews the literature on IS and blockchain, section "Results" presents the preliminary two-step framework, section "Discussion" links theory to practice with an analysis of some field experiences, while the last section "Conclusion" completes this working paper outlining the next research steps.

Materials and methods

Industrial symbiosis

Although IS is a topic already mentioned by Renner (1947), a turning point occurred when (Frosh and Gallopoulos 1989) wrote about "industrial ecosystems." The same year, what is now called "the industrial symbiosis of Kalundborg" was discovered in Denmark and, then, published in international articles by Knight (1990) and Barnes (1992). Ayres (1989) wrote about the "biosphere versus technosphere" metaphor, stating that technosphere can design and manage its processes following the example of the biosphere, improving efficiency and reducing the release of unused by-products into the environment. The most prevalent definition of IS was published by Chertow (2000): "industrial symbiosis engages traditionally separate entities in a collective approach to competitive advantages involving a physical exchange of materials, energy, water, and by-products." Chertow underlined that the keys for IS are the collaboration and the synergistic possibilities offered by geographic proximity. To distinguish IS from other types of resource exchanges, Chertow (2007) proposed a minimum criterion for IS networks, i.e., the "3-2 heuristic," that considers at least three different actors and at least two categories of resources. Posteriorly, Lombardi and Laybourn (2012) proposed an updated definition of IS, considering it as a business tool for sustainable growth in which geographic proximity is neither necessary nor enough. Cutaia and Morabito (2012) classified IS networks into three main models: (1) the bottom-up approach, i.e., self-organized activity or district resulting from spontaneous interactions among companies; (2) the top-down approach, i.e., structured networks or eco-industrial parks (EIPs) developed from a scheduled plan for a specific industrial area; (3) facilitated networks characterized by an enabler who supports the activities of matching resources and managing the resources synergies. Domenech et al. (2019) identified some common features of the bottom-up networks (1), i.e., the involvement of companies at a local level or in the same industrial area; the affiliation to the manufacturing and primary industrial sector; the development in countries with rigorous environmental policies and with high awareness on sustainability; the frequent inclusion of private firms supported by the local government. The most cited example of self-organized networks, but also of IS in general, is the eco-industrial system of Kalundborg. Starting from 1961, six private and public entities of the city of Kalundborg, in Denmark, chose spontaneously to share resources surpluses, such as steam, heat and gas. During the last decades, new entities joined the IS network, by taking advantages to close resources loops. Figure 1 represents the temporal evolution of Kalundborg symbiosis exchanges from 1961 to 2009. Tangible benefits examples of all symbiosis industries include the reduction in the use of more than 30 million m^3 of groundwater and 7.6 million m^3 of surface water (Jacobsen 2006).

Second proposed IS model (2) concerns EIPs, i.e., examples of the application of industrial ecology principles in a specific location. The cooperation among a group of businesses and the efficient sharing of resources, like water, energy, material, information, infrastructures, services, are key features for EIPs, leading to economic, environmental and social gains for the entities of the network and also for

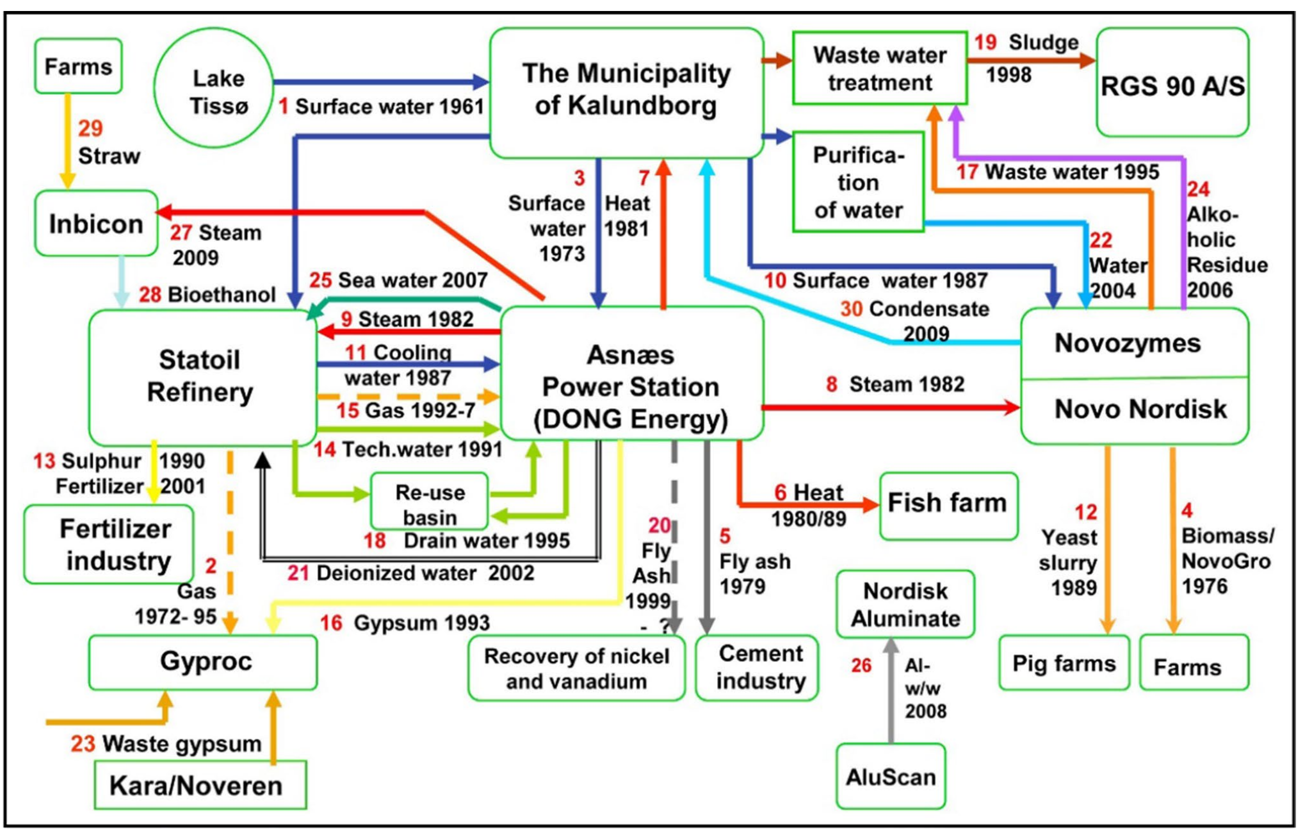

Fig. 1 Temporal evolution of Kalundborg symbiosis exchanges from 1961 to 2009 (Branson 2016)

the local community nearby. Relevant initiatives of EIPs are located in America, Asia and Australia (Lowe 2001; Liu et al. 2018; Domenech et al. 2019). The corresponding Italian model of an EIP is called Environmental Equipped Industrial Area (EEIA) and manages the environmental services linked to the industrial activities in an integrated way, simplifying the administrative formalities (Cutaia and Morabito 2012). The last group of IS models (3) are the facilitated networks. These foster the matching of demand and supply of resources among parties who would not otherwise have the opportunity to interact. The most cited example of facilitated networks is the National Industrial Symbiosis Program (NISP) in the UK, i.e., the first national IS program, replicated in many regions and countries after its launch in 2005. NISP is a network of associates that investigates on technological and commercial territorial opportunities to exchange resources, materials, energy, water, logistics and expertise, with the support of intermediaries or facilitators. The success of NISP lies in the national synchronized operational focus supported by a local implementation framework (Mirata 2004; Cutaia et al. 2015; International Synergies 2021). In this direction, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) established a methodology for the creation of IS networks and developed a supporting online platform for Italian companies in 2011. The methodology aims at looking for IS synergies in a specific regional territory combining different databases. Three main steps are necessary, i.e., the organizational, to involve a group of regional companies; the executive, to facilitate working tables among companies to collect information about input–output resources; and the final phase, to deliver a manual to companies with the overview of the potential enabling synergies (Cutaia et al. 2018). The platform is named "Symbiosis®", and it represents the first Italian digital platform for IS to support companies to identify opportunities at a regional level. The platform is based on a web interface where users register company data, add geo-referring information, then insert, update, manage data about their by-products or services, and look for potential IS synergies with other local firms (Industrial Symbiosis platform 2021).

Although the creation of IS opportunities provides a wide range of benefits, i.e., new business opportunities, economic gains, increasing competitiveness, improvements in environmental performances, reduction of disposal costs, savings in virgin materials, creation of further jobs, and reduction in waste volumes produced, practical implementations of IS networks are still limited. Several reasons exist that hinder the adoption of IS practices. Taking part into an IS network is an investment of financial resources and time. Then, cultural, managerial, technological, legislative barriers affect decision making, such as the lack of information and awareness of IS concepts, lack of technical and organizational expertise, low trust in cooperating with other companies, limited support or incentives, uncertainty in regulations and policies for by-products exchanges, lack of information technology (IT) infrastructures, difficulties in sharing data (Neves et al. 2020; Ponis 2020).

In recent years, the scientific literature showed increasing interest in developing tools, methods and quantitative models to manage the complexity of IS networks and to offset some of the abovementioned weaknesses. Lawal et al. (2021) identified two main branches for classifying IS tools, i.e., process integration (PI) methods and mathematical optimization (MO) models. PI methods aims at minimizing the use of resources and harmful emissions in single or multiple industrial plants. The analyses can focus on heat, water, carbon, waste, power or production planning of the plants, including also pinch analysis (PA). MO models consider all the resources simultaneously, i.e., energy, water, power, carbon and waste, within IS networks, with the aim of optimizing their consumption and managing material flow. MO models for IS are mainly based on supply chain network design and management models that aim at simultaneously optimizing stock, economic and environmental issues (Bortolini et al. 2022a; Ventura et al. 2023b). Yeo et al. (2019) stressed the fragmented nature of qualitative and quantitative tools available supporting IS creation. To classify IS tools, the authors identified different IS creation steps, i.e., preliminary assessment, engage businesses, find synergy opportunities, determine feasibility, implement transactions and documentation. Digital technologies and intelligent algorithms occupy a predominant portion for future research developments to support identifying innovative, environmental responsible and synergistic IS process chains. I4.0 is profoundly influencing IS, especially IT-related technologies. Sensors, IoT and data analytics, are expected to boost the efficiency of circular material flows by data (Järvenpää et al. 2021). In this context, digital platforms have an engagement role for firms by generating networks effects and by enabling real-time information exchange. The creation and the management of synergies among firms are facilitated by digital platforms (Aquilani et al. 2021). Smart online platforms support the by-products and resources sharing, and the technical requirements ensure security of information exchange, robustness and reliability of data (Chalkias 2019). Blockchain technology can play a role in digital platforms for IS management, enhancing trust among participants and reducing information asymmetry.

Blockchain technology

Blockchain is part of the enabling technologies powering I4.0. The relevance of blockchain technology resides in one of the main agendas of I4.0, i.e., the ability to enhance the level of information integration across multiple actors and supply chains in a secure and verifiable way (Esmaeilian et al. 2020). Blockchain is mentioned in the European Circular Economy Action Plan 2020 among the digital technologies that "will not only accelerate circularity but also the dematerialization of our economy and make Europe less dependent on primary materials," also promoting their use "for tracking, tracing and mapping of resources" (European Commission 2020). The term "blockchain" refers to how transaction data are stored: blocks containing data are linked together to create a chain. Each block has a hash or a unique identifier, timestamped groups of valid transactions and the previous block's hash, to avoid the alteration of any block in the chain. In this way, the blockchain is tamper evident. When a new information is added to the blockchain, a protocol ensures that only valid transactions can be added, and all the nodes must agree. The complex calculation required to create each block, i.e., the proof of work, excludes the need of a centralized authority for establishing trust and preventing fraud by hackers. Cryptographic keys, hashing and digital signature, make blockchain technology one of the most secure tools available on today's market (Zheng et al. 2017; Gupta and Bedi 2018). There are different typologies of blockchain considering access regulation, permissions, kinds of incentives and operation modes. Depending on the access regulation to the blockchain system, public blockchain, private blockchain, consortium or federated blockchain exists (Garzik 2015). Based on permissions to access data within the system, permissionless blockchains and permissioned blockchains are two popular technology environments (Kouhizadeh et al. 2019). Regarding the kind of incentives, tokenized blockchains and non-tokenized blockchains are two distinct solutions (Narayan and Tidström 2020). Finally, according to the operation mode, logic-oriented blockchains and transaction-oriented blockchains exist (Szabo 1997). Nowadays still many obstacles preclude the transformation of the technology value of blockchains into business value. The most relevant barriers affect the technological, organizational, economic and legal domain. The immaturity of blockchain technology creates challenges that include scalability and usability. The technology adoption is hindered also by the lack of technical capabilities; complexity and accessibility to IT infrastructures are considered. Then financial constraints, lack of commitment and support from the management, and the difficulty in changing organizational culture represent firm concerns (Kouhizadeh et al. 2021). The few applied use cases include different sectors (Zheng et al. 2018), e.g., supply chain management and logistics (Saberi et al. 2019; Blockchain Council 2021), retail fashion (Wang et al. 2020; ConsenSys 2021), IoT, healthcare, financial, governance, digital identity management (Sharma 2020), social impact (UNSDG 2022).

Industrial symbiosis and blockchain technology

Each supply chain reflects a complex network of business relationships in the process of creating and delivering value. Transparency and trust are generally limited in a traditional supply chain. Exchange of information among distant partners may require resources, intermediaries and time. Most transactions are still paper based, so opportunities for fraud, asymmetric information and inefficiencies are frequent. In addition, coordination among stakeholders belonging to the supply chain is another pressing issue. Although enterprise resource planning (ERP) solutions and digital tracking devices are employed, the complexities and errors are still frequent (Kshetri 2019; Amiri et al. 2022). In this context, emerging technologies linked to I4.0 are developing new business opportunities for supply chain networks. Blockchain makes easier to track every step by auditing the entire chain without or with fewer intermediaries (Bhalerao et al. 2019). Due to the ability to integrate data from multiple sources, blockchain technology can be a solution for supply chain issues to simplify the exchange of information among firms and business networks by forcing them to adopt a universal language to build strategic and beneficial relationships. Significant improvements in mapping, auditing and certifying supply chains are made with blockchain to win the trust and confidence of final consumers (Kouhizadeh et al. 2019). Supply chain management is supported through three main aspects: (1) transparency, as blockchain is transparent by nature, i.e., the ledger is decentralized and shared among all the nodes of the network; (2) traceability, since all transactions are tracked, linking all the stakeholders of the supply chain; (3) authentication, because each participant of the network validates, approves and archives the transactions (Wang et al. 2020). Supply chain transactions recorded on blockchain may be created automatically by smart contracts or saved by automatic electronic sensors like IoT devices. Smart contracts formalize, automate and secure relationships over computer networks, by combining protocols with user interfaces (Szabo 1997; Christidis and Devetsikiotis 2016). In recent years, some multinational companies chose to integrate blockchain within their supply chains, e.g., Carrefour, Walmart, Nestlé, Alibaba (Kshetri 2019; Wang et al. 2020).

Blockchain brings also advantages in CE domain (Alexandris et al. 2018; Tseng et al. 2018; Nandi et al. 2021) and waste management (Gupta and Bedi 2018; Kouhizadeh and Sarkis 2018; Kouhizadeh et al. 2019; Sen Gupta et al. 2022). The transition toward CE can be facilitated by integrating and sharing information along the entire supply chain to exchange of material or by-products, offering security in managing online data, ensuring access information to all the supply chain members, improving collaboration among the supply chain participants. In waste management, waste exchange programs are critical and require collaboration among entities. Manipulation and fraud, lack of information or knowledge and manual processing are all current concerns: blockchain technology can be helpful to solve or reduce them.

Similarly to the advantages that blockchain can provide supply chains, CE and waste management, IS could benefit from this technology as well. Blockchain and IS can both be considered as networks, ecosystems and platforms. Blockchain is a distributed peer-to-peer network where data are stored and shared among participants of a digital platform, while IS is a network of companies where resources are generally transferred through the support of a platform, following CE principles. Both are characterized by the presence of actors that collaborate for the development of an ecosystem and for the implementation of synergies, by exceeding what can be achieved by the single parts. Today IS and blockchain technology are facing similar challenges, such as the lack of information infrastructures, procedural and technical difficulties in data collection, the lack of willingness, trust and cooperation among companies and challenges in customizing digital solutions to case studies (Egger 2020). Considering IS and blockchain together might allow to overcome some of their existing limitations. Sensitive information about IS waste streams is difficult to gather because data about production processes represent a competitive advantage for companies, amounts of waste give details regarding the volumes sold, and pricing is a fundamental part of negotiation processes (D'Hauwers et al. 2020). The use of blockchain technology in IS networks can address challenges with information infrastructure, providing a robust and trustworthy system based on traceability, transparency and unchangeable of data. Even though much research efforts are highlighting the potential of blockchain technology in IS networks and CE contexts, only few studies link specifically this technology to IS in academic literature (Nallapaneni and Chopra 2020; Ponis 2020; Gonçalves et al. 2021; Godina et al. 2022).

Results and discussion

This section proposes a procedural framework consisting of two steps that support the decision-making process regarding the integration a blockchain platform in IS networks (Ventura et al. 2021). The initial step includes a conceptual scheme assessing five domains—technological, economic, social, environmental and legislative—with the aim of providing a logical pattern for the potential application of blockchain technology in circular business networks. The subsequent step gathers the insights obtained from the previous one, adopting a more operative approach. This step delineates a practical and prospective scenario in the event that blockchain is effectively implemented in an IS network.

First step: conceptual framework

The conceptual framework includes the following sections of assessment: technological, economic, social, environmental and legislative. Each section incorporates distinct factors, as well as related tools, Key Performance Indicators (KPIs) and benchmarks, aimed at evaluating the feasibility of introducing blockchain technology into an IS network. Figure 2 illustrates a sunburst diagram, depicting the necessary elements for a feasibility analysis. At the center of the chart, a network of firms, i.e., the IS system connected by blockchain technology, is represented, symbolizing its alignment with different external factors.

Technological branch

The technological branch considers:

- The existing company IT systems, such as software, informational systems, platforms that can be incorporated with the new technology or that, otherwise, can hinder the integration of blockchain;
- The scalability issues, due to the high number of transactions that can be processed in a wide network of IS, which can cause delays in processing the large amount of data; in other words, blockchain has a low throughput with the increase of the network size (Alshahrani et al. 2023);
- The level of technological development of all the stakeholders involved, as it can make complex the adoption of the new technology.

The identified tools to support this phase include an information technology consulting and established technological rates, indicators and benchmarks for assessing the digital development of stakeholders, the values of which may be compared with the industry average.

Economic branch

By analysing the economic branch, the integration of blockchain technology into IS can be considered as an investment of resources project. Because of that, to consider the investment as profitable, expected costs of the use of blockchain have to be lower than the current costs of an IS network management. Current costs include all the expenses incurred for the development and management of an IS network without considering blockchain. They include expenses of verification of the parties, goods or services, contractual arrangements, costs of networking related to the development of management platforms and their operational costs (Catalini and Gans 2020). With the introduction of blockchain technology into IS, new costs must be considered: the cost for

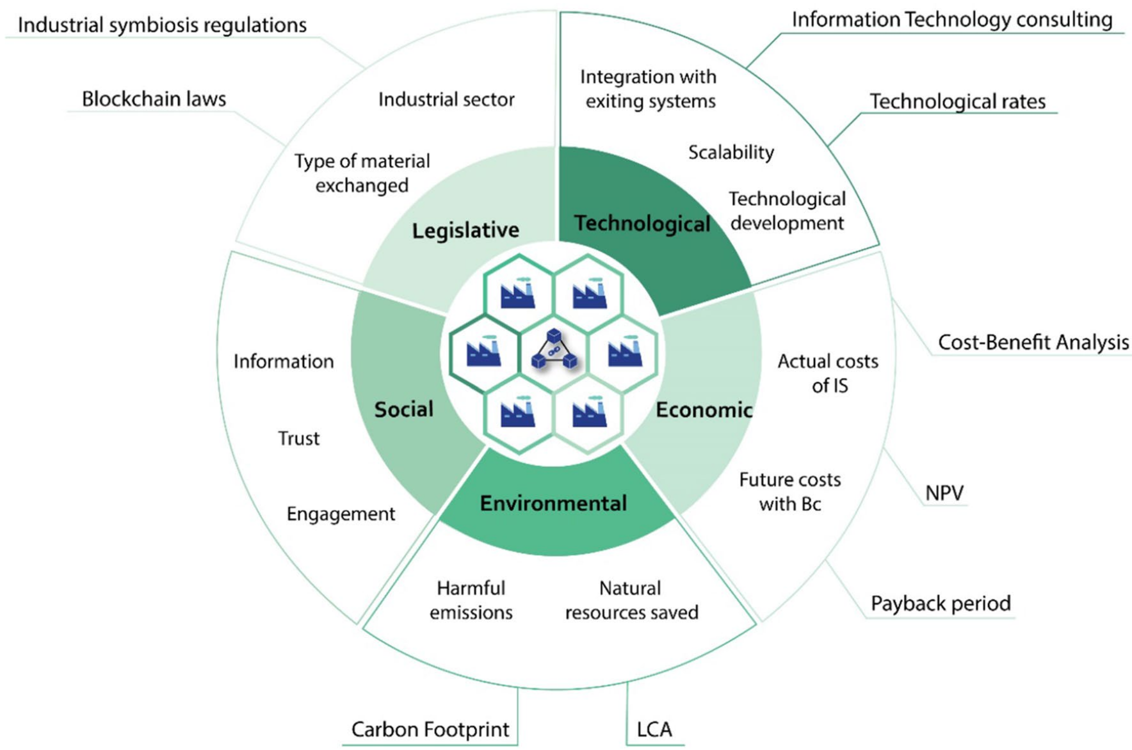

Fig. 2 Conceptual framework of the feasibility study for introducing blockchain technology into IS (Ventura et al. 2021)

the development of a customized blockchain platform, costs of IS which remain stable and saved opportunity costs. Since blockchain is a feature-dependent technology, the future expected costs of the project will vary in accordance with the requirements and they depend on various factors, from the complexity of the project to the selected software company. Cost of blockchain implementation is allocated in multiple phases of the project, including design, development, coding and testing, deployment, migration, i.e., moving the existing solution to the new platform, maintenance, upgrade and third-party tools, like hosting, storage and collaborations. In addition, other costs to consider are the fees to pay to the app developer for using the blockchain platform and costs per transaction, the cost of project management, energy costs and the cost of hiring a team, which will change depending on whether it is an in-house team, a free-lancer or agency. At the same time, there are some costs of IS that remain stable, mainly operative costs, such as those related to meet and involve companies in workshops and logistics expenses to trade by-products. Despite the significant investment that the implementation of a blockchain platform into IS entails, several costs can be reduced or entirely eliminated, by deducing them from the total amount of costs. Blockchain is therefore considered cost-effective because, by reducing the need for mediators and aiding the verification of transaction elements, it eliminates the costs of verification, so less oversight is needed. The cost of networking is also reduced by using Initial Coin Offering (ICO), i.e., a form of crowdfunding that use cryptocurrencies, or selling tokens for financing the development of a new platform and its operational costs (Esmaeilian et al. 2020). Moreover, other costs can be saved: expenses of duplication of efforts are removed because all members of the network have access to the shared ledger and costs related to regulatory processes are reduced, together with costs for delays due to missing paperwork. Blockchain, in general, improves business processes efficiency, reducing bottlenecks and optimizing current manual procedures. Table 1 summarises the as-is and to-be costs cited above. The recommended tools for this branch refer to investment analysis: net present value (NPV), cost–benefit analysis, payback period.

Environmental branch

Regarding the environmental branch, the blockchain technology can improve efficiency in processes that help to achieve sustainable goals, enhancing the transparency of data and the management of resources, tracking them among the whole life cycle. However, as stated in several studies, Bitcoin is well-known for being energy demanding because of the proof of work algorithm, on which blockchain is based (Vranken 2017; Alshahrani et al. 2023). The debate on the consuming of energy of blockchain is still open, but the discussion can therefore delay the adoption of the technology.

Table 1 Overview of as-is and to-be costs of introducing blockchain into IS networks

As-is: costs of industrial symbiosis	To-be: costs of blockchain and industrial symbiosis
+ costs of verification (parties, goods or services, contractual arrangements)	+ costs of IS (total costs of as-is scenario)
+ costs of networking (developing platforms, operating platforms)	− saved costs (costs of verification, costs of networking, more efficiency)
+ costs for data collecting	+ costs of blockchain (platform implementation, energy consumption, hosting or other fees)

For these reasons, when considering IS networks, which is based on CE and sustainable principles, it is necessary to estimate the impact of blockchain on the environment, the harmful emissions that its adoption involves, and, at the same time, whether the introduction can save natural resources. Environmental indicators can support this analysis, such as the LCA and the carbon footprint methodology.

Social branch

The adoption of blockchain technology into IS should also consider social factors that can influence the success of the investment. For example, if the participants of the blockchain network trust each other and there is already an entity that manage the interactions among them, blockchain may not be the appropriate tool. Otherwise, if relationships among participants are vulnerable and opportunistic behaviors are frequent, blockchain will enhance trust among them and, since every transaction or data are shared and verified, the members of the network are incentivized to share by-products or resources. In this regard, smart contracts can be developed on a blockchain in order to verify that all the obligations of a contract between two parties will actually be fulfilled. Another aspect to consider is the information exchange among IS partners because it is one of the main barriers for the development of the network, due to the difficulty in protect sensitive data, asymmetric and misaligned information and cooperation problems (Zyskind and Nathan 2015; D'Hauwers et al. 2020). Data within blockchain are visible to all actors and updated in real time, so the information sharing is maximized with this technology. Finally, engagement is fundamental for both blockchain and IS network. In a transparent environment where all transactions are evident to every member of the network, the engagement of each company grows, benefiting the balance of the platform and promoting IS synergies. The link between IS and blockchain network is an incentivization system using token: these coins can be used in blockchain platforms for encouraging green behaviors (Esmaeilian et al. 2020). The system can reward IS actors who share a certain amount of waste or by-products inducing them to share more and more resources.

Legislative branch

The last group of factors to consider is related to the legislative branch. Both IS and blockchain network must compliance with the law, in respect of two main aspects:

1. The industrial sector to which the company that sends waste or by-products belongs, since the main issues concentrate on waste and by-products management;
2. The type of material to be transferred.

After considering all necessary technological, economic, environmental, social and legislative aspects, the outputs should be collected and evaluated. If the introduction of blockchain is judged convenient by a theoretical perspective, then the second step is considered, allowing to operatively visualize how blockchain elements can potentially support an IS network.

Second step: operative framework

Following the initial step, after gathering the insights from the conceptual framework, an operative framework is proposed to establish a connection in practice between the IS network actors and the blockchain elements. Figure 3 represents a guideline for the IS network design joining the main features of a blockchain platform.

Figure 3 outlines a potential to-be scenario constituted by a network of companies connected through a blockchain platform. Two manufacturing companies that generally convert inputs into outputs are examined. Each company, through the digital platform, can share data concerning its input needs, waste and by-products to dismiss. According to the founding principles of IS, waste generated by one company's end-of-line is transferred to another company, where it becomes an input, usually after a reprocessing phase. Within this framework, smart contracts are an essential tool for mediating relationships among different organizations. The execution of smart contracts on the blockchain platform can simplify the approval of procedures from multiple actors of the supply chain that usually suffers from risk of fraud and loss. An accessible and secure digital version of the contract is sent to the involved parties and automates complex manual processes. Another

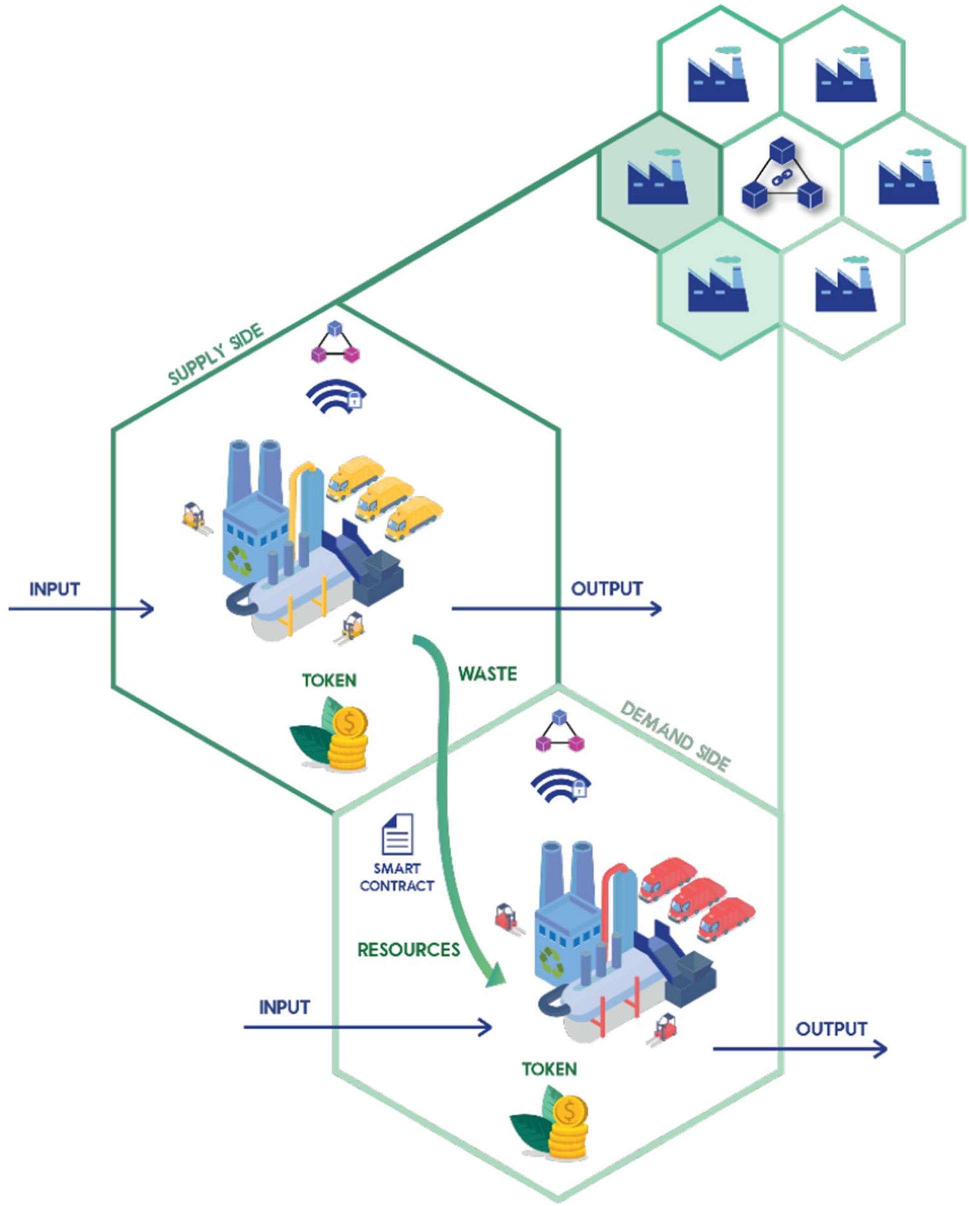

Fig. 3 Operative framework of an IS network blockchain-based (Ventura et al. 2021

element introduced within the new system is a mechanism for incentivization by using digital tokens. When industrial waste is repurposed and transferred to another company that incorporates it as a secondary raw material, a specific quantity of tokens is awarded to both supply and demand side. This tool plays a fundamental role in motivating participants to foster synergies with available resources, as well as enhancing their commitment to the IS network (Kouhizadeh et al. 2019; Esmaeilian et al. 2020; Narayan and Tidström 2020).

Discussion

The scientific literature is only starting to investigate the field of blockchain within IS networks. Several challenges still exist, such as the limited accessibility of most digital platforms to the public, the scarcity of robust information infrastructures, the lack experts to provide operative support to implement blockchain, the heterogeneity of data to collect, storage and transfer, the lack of willingness, trust and cooperation among companies, and also the customization of digital solutions for specific case studies (Egger 2020). The integration of IS and blockchain has the potential to address certain existing limitations. Implementing blockchain technology can help with coordination issues within IS networks, particularly when dealing with a high number of firms. Additionally, it has the capability to automate tasks currently carried out by human operators, thereby reducing the susceptibility to errors. By facilitating information exchanges and enhancing transparency, blockchain strengthens trust among participants in IS networks.

The proposed framework aims at investigating the use of blockchain technology within IS networks, by a conceptual and an operative perspective. The conceptual framework represents the first step for assessing the factors for a preliminary feasibility study. Considering technical and economic aspects is not sufficient, as legal regulations, the social dimension and, undoubtedly, environmental impacts also affect the decision-making process. Besides factors, the framework suggests tools, benchmarks and indicators to support the management of every area separately. Once a positive overall evaluation of the conceptual framework is made, a more operative framework constitutes the second step. The basic idea is to visualise the main elements of an IS network together with blockchain technology. Given two companies that share resources within an IS network, their relationship can be regulated by smart contracts and by an incentivization mechanisms of digital tokens to award demand and supply side for every IS synergy implemented.

The main strengths, weaknesses, opportunities and threats (SWOT analysis) associated with the implementation of blockchain technology in a regional IS network are collected in Fig. 4. The SWOT analysis collects information from the reviewed papers to build the two-step framework and from experts in the environmental field.

The SWOT analysis can be considered as a decision-making tool for IS networks to overcome barriers and boost enabler factors for IS and blockchain implementation. Internal factors refer to the strengths and weaknesses of the companies involved in the potential IS network, while external factors are related to opportunities and threats that they might encounter in the environment, i.e., legislation, sociocultural or changes in the market. The SWOT analysis factors in Fig. 4 are order by relevance, i.e., factors in position (1) represent the most helpful or the most harmful aspects for blockchain implementation in IS networks, factors in position (2) have a medium impact, while factors in position (3) are the least impactful according to the analysis. As helpful internal factors, the willingness to cooperate is fundamental for implementing IS networks (Chertow 2000; Domenech et al. 2018; Neves et al. 2019). Companies should leverage their openness toward cooperation together with their expertise and corporate knowledge about new digital technologies and environmental sustainability (Ponis 2020; Kouhizadeh et al. 2021). Concerning harmful internal factors, the adoption of IS principles and blockchains might face resistance to change from participants who are familiar with traditional supply chains. This obstacle could significantly affect the projected outcomes (Godina et al. 2022). Then, the lack of resources and technical competences, especially in presence of small- and medium-sized enterprises, represent another factor that makes it difficult to integrate blockchain into existing systems and to participate in IS projects. Lastly, if regulations do not support innovations and internal data policies are stringent, the implementation is rarely practicable (Ponis 2020). The external factor that plays a pivotal role for IS projects and for the potential application of blockchain technology is the presence of facilitators. The role of ENEA in Italy as third party in IS regional projects has been strategic for the IS diffusion in the last decade, through the Italian network for IS called SUN—Symbiosis Users Network and a new methodology to boost the application of

Fig. 4 SWOT analysis for the implementation of blockchain technology in an IS network

Blockchain & Industrial Symbiosis networks	**HELPFUL**	**HARMFUL**
INTERNAL FACTORS	STRENGHTS S1: Willingness to create partnerships S2: Business expertise S3: Corporate knowledge	WEAKNESSES W1: Resistance to change W2: Lack of resources and competences W3: Strict data policy
EXTERNAL FACTORS	OPPORTUNITIES O1: Support of facilitators or advisors O2: External sources of finance O3: Environmental awareness	THREATS T1: Regulatory constraints T2: Lack of infrastructures T3: Low network engagement

IS in Italian regions (Cutaia et al. 2015, 2018). In addition, external sources of finance offered by national or international authorities can facilitate the use of technologies in IS networks, given the difficulties of companies in investing their own resources for innovations. Funding opportunities provided by the states can encourage IS initiatives and supporting digital platforms (Järvenpää et al. 2021). The last external helpful factor is represented by the increasing global awareness about environmental issues and the harmful impacts of human activities on the planet. As result, the positive trend of people's interest on environmental concerns is leading to implement new paradigms for tacking climate change and reducing waste. This is therefore an aspect to be taken into account when implementing innovative tools for IS (Valentine 2016; Sonel et al. 2022). As main external threat that influences the development of IS and blockchain technology, it is worth mentioning existing regulation constraints. The lack of coherence between policies, the limited knowledge in regards of IS and blockchains and the lack of shared international visions may hinder the expected results (Domenech et al. 2018; Lybæk et al. 2021). In the end, both logistics and technology infrastructures are crucial for blockchain-based IS networks implementation (Ponis 2020; Godina et al. 2022), along with the engagement of the network that could hinder its expansion and development if not properly fostered (Esmaeilian et al. 2020; Aquilani et al. 2021). The overall strategy suggested by the SWOT analysis is to leverage the internal factors, especially the willingness to create partnerships and the business expertise, to overcome the main common weaknesses of a company that relate with the resistant to change and the investment of time and resources for new incoming projects. The support of a third party as IS facilitators and the funding opportunities offered by the national authorities, can contrast the harmful external constraints represented by the policies and the lack of appropriate infrastructures.

Numerous research endeavors emphasize the potential of blockchain technology in promoting sustainability within supply chains or CE contexts. However, the existing literature refers to only a limited number of real cases that integrate blockchain technology in IS networks. Nallapaneni and Chopra (2020) propose an industrial-based multi energy system as a network of firm that exchanges energy flows in several forms, reducing costs for purchasing energy and boosting green performance. In order to prevent cascading failures into the network, the authors propose the use of the blockchain-based online information sharing platform, where an IS relationship among firms is considered feasible thanks to the blockchain-based smart contracts. The total resilience of the network is therefore reinforced by the capacity of the platform to create firm-to-firm IS relationships and avoid energy breakdowns. Ponis (2020) introduces an innovative business-to-business (B2B) marketplace based on blockchain technology for creating symbiotic relationships among manufacturing firms in Greece. In this context, blockchain acts both as a trust mechanism and an exchange platform. The research conducted by the author is structured in a series of action steps, represented in Fig. 5.

Gonçalves et al. (2021) present a blockchain architecture for supporting the IS process of the pulp, paper and cardboard production sector of Portuguese companies. To provide trust and transparency among the entities, smart contracts and hyperledger fabric are used for building a permissioned ledger, characterized by scalability and modularity. The gap between the current literature dedicated to blockchain technology and the few studies about practical applications of this topic within sustainability issues is still an urgent challenge. The necessity of experimental evidence of the sustainability gains of blockchain technology efforts, I4.0 optimization techniques in CE practices and the need of defining globally applicable methodology for integrating IS and blockchains are all examples of research needs that require immediate attention (Tseng et al. 2018).

Conclusion

Blockchain emerges as a promising and powerful technology to consolidate industrial symbiosis (IS) in the contemporary hyper-connected and real-time industrial context. In this paper, its potential is revised, and a preliminary two-step framework is proposed to support decision makers and practitioners in the design and management of green circular supply chains. In the first step, named conceptual framework, five categories of assessment are stressed, i.e., technological, economic, social, environmental and legislative. The subsequent second step, named operative framework, practically promotes synergies among supply chain nodes toward circular economy (CE) principles and the valorization of by-products, with the use of blockchain. The framework allows highlighting open challenges and opportunities, discussed in this paper together with the involved stakeholders. The main limitation of the study is the absence of an application of the technology to a case study. The implementation of the proposed framework to a specific set of companies located in a defined region would contribute to better understand the effectiveness of blockchain technology in an IS network.

Even though a robust basis and acceptance of the IS concept are already in place at the institutional level, several measures are essential to generate commitment among stakeholders. The digital challenges mentioned in this paper, along with quantitative methods and multi-target approaches, represent the anticipated next steps in this field.

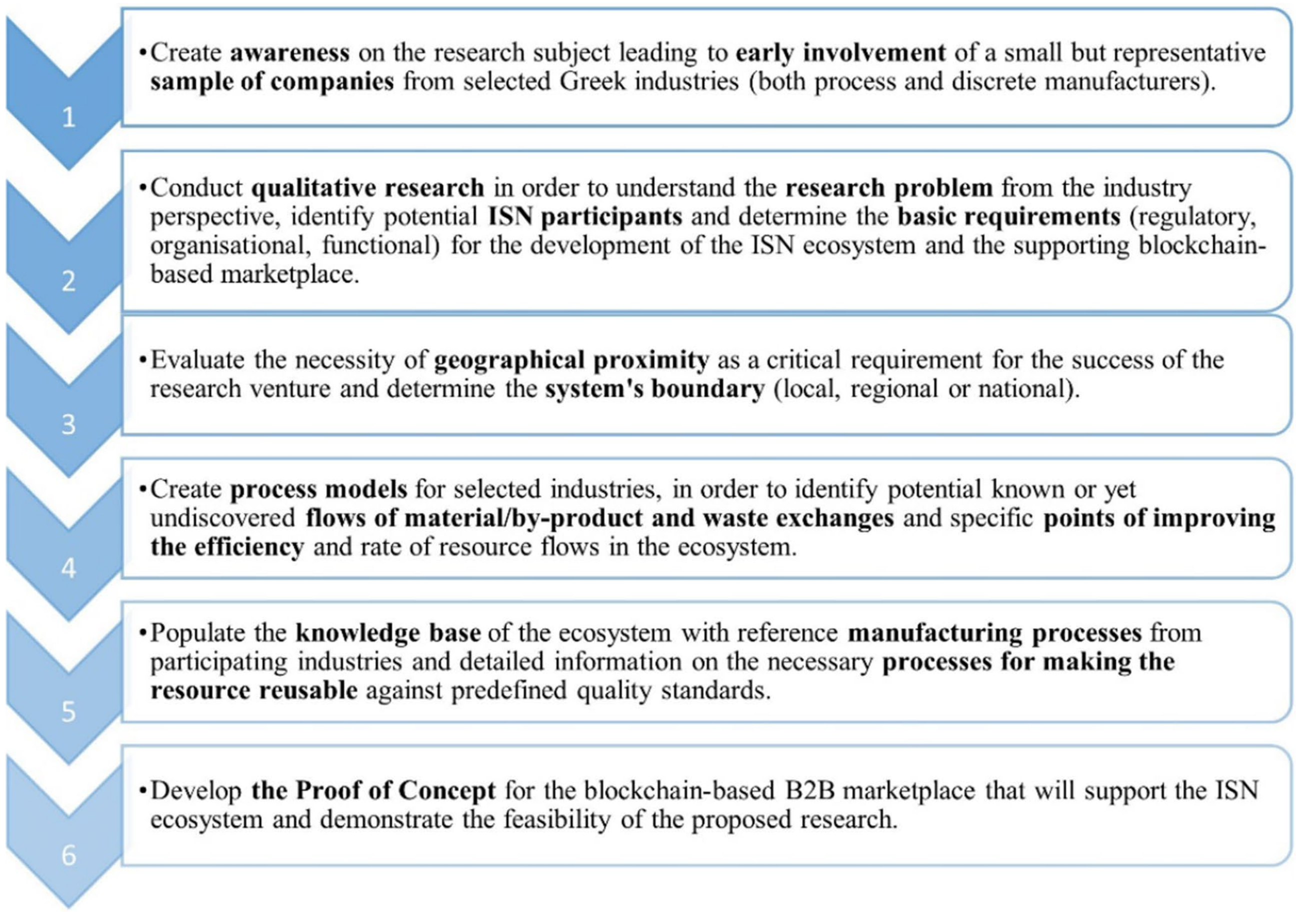

Fig. 5 Action steps to implement a B2B marketplace based on blockchain technology based on Ponis (2020)

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Declarations

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