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ORIGINAL RESEARCH

A blockchain architecture with smart contracts for an additive symbiotic network - a case study

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Abstract
Adopting innovative technologies such as blockchain and additive manufacturing can help organisations promote the development of additive symbiotic networks, thus pursuing higher sustainable goals and implementing circular economy strategies. These symbiotic networks correspond to industrial symbiosis networks in which wastes and by-products from other industries are incorporated into additive manufacturing processes. The adoption of blockchain technology in such a context is still in a nascent stage. Using the case study method, this research demonstrates the adoption of blockchain technology in an additive symbiotic network of a real-life context. The requirements to use a blockchain network are identified, and an architecture based on smart contracts is proposed as an enabler of the additive symbiotic network under study. The proposed solution uses the Hyperledger Fabric Attribute-Based Access Control as the distributed ledger technology. Even though this solution is still in the *proof-of-concep*t stage, the results show that adopting it would allow the elimination of intermediary entities, keep available tracking records of the resources exchanged, and improve trust among the symbiotic stakeholders (that do not have any trust or cooperation mechanisms established before the symbiotic relationship). This study highlights that the complexity associated with introducing a novel technology and the technology's immaturity compared to other data storage technologies are some of the main challenges related to using blockchain technology in additive symbiotic networks.

Keywords Circular economy · Additive symbiotic networks · Blockchain technology · Blockchain architecture · Smart contracts · Case study

1 Introduction

1.1 Additive symbiotic networks

The public pressures on environmental assets, the higher levels of competition, and the strict regulations have pushed firms to include environmental concerns in their strategic planning (Manupati et al. 2020) and gradually adopt circular business models (Maranesi and De Giovanni 2020). The circular economy has become a recommended approach to economic growth aligned with self-sustaining, productive systems (Genovese et al. 2017). Its primary focus is closing the loops in industrial systems by returning residual wastes (and other resources) to production processes through shifting classical production business patterns from linear to circular (Husain et al. 2021; Nikolaou et al. 2021). Industrial symbiosis falls under the circular economy's approach, being recognised as a strategy to support the transition from

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a linear to a circular economy (Yazan and Fraccascia 2020; Abreu and Ceglia 2018). According to Yazan and Fraccascia (2020) and Ponis (2021), industrial symbiosis networks aim to improve resource efficiency by transforming waste streams and other resources into new value-added products or materials that can be further used in other processes. This exchange of resources between independent but interconnected organisations creates a value network composed of different stakeholders exchanging value flows between them that are designated by industrial symbiosis networks (Albino et al. 2016; Ponis 2021).

Industry 4.0 has been identified to potentially provide opportunities to unlock the implementation of circular economic systems (Xin et al. 2022; Rajput and Singh 2019b), and it has been defined as an integration of real-time communication and digital technologies to automate manufacturing systems and achieve precision, accuracy, and a higher degree of automatisation (Järvenpää et al. 2021; Rajput and Singh 2019a). Despite the relevance of this topic, there is a need for studies that evaluate Industry 4.0 technology-related uncertainties and circular economy (de Lima et al. 2021). Additive manufacturing (also commonly designated by 3D printing) has been considered a critical driving force behind Industry 4.0 (Ponis et al. 2021; Tavares et al. 2020). It has been highlighted as a technology that could significantly change the economy due to its potential to encourage repair and remanufacturing activities, reduce production wastes, reduce obsolescence risks and inventory costs, and consequently, be an enabler of the circular economy (Kravchenko et al. 2020). The literature provides evidence of the intersection between additive manufacturing and the circular economy. For example, Gaikwad et al. (2018) have proven that it is possible to regenerate plastic from electronic waste into sustainable filaments for use in additive manufacturing. Zander (2019) shows the increasing interest in using recycled plastics in material extrusion additive manufacturing, emphasising the low rate of plastic recycling, estimated at approximately 9.5%. Shanmugam et al. (2020) explored the opportunities for using recycled polymer (plastic) materials in additive manufacturing processes and their ability to accommodate a design towards a circular economy. Kunovjanek and Reiner (2020) showed that additive manufacturing could directly reduce raw materials inventory by approximately 4%. Furthermore, Ferreira et al. (2021) have demonstrated the potential to develop industrial symbiosis networks within the additive manufacturing industry, stressing the current use of waste streams from other industries (external wastes) as inputs for additive manufacturing processes. Even though only a few recent studies have focused on these intersections (Ferreira et al. 2023a; Hettiarachchi et al. 2022).

Thus, considering the potential of additive manufacturing technologies to use or incorporate waste streams in its processes, industrial symbiosis networks may potentially arise within this context, promoting the exchange of resources between different industries or sectors. These industrial symbiosis networks in which wastes are used in additive manufacturing processes as material inputs are designated by additive symbiotic networks (Ferreira et al. 2023a)As industrial symbiosis networks, these additive symbiotic networks can be understood as value networks constituted by several stakeholders. Among the different actions that can occur within a symbiotic relationship, this study focuses on the exchange of wastes between various stakeholders, specifically plastic wastes that appear in urban waste streams and that can be used to produce recycled filament for 3D printers.

1.2 Industrial Symbiosis Networks and Blockchain Technology

Another Industry 4.0 technology enabling the implementation of circular systems is the blockchain (Mukherjee et al. 2022), introduced by Nakamoto (Nakamoto 2008) and primarily used to support the existence of the Bitcoin cryptocurrency. Still, since then, it has gained recognition and is globally used (Zheng et al. 2018). A blockchain or blockchain technology refers to the concept in which a system uses cryptographic mechanisms to relate the integrity of future data blocks to past data blocks, hence creating a chain of blocks (Han and Rani 2022; Morkunas et al. 2019). It is also referred to as Distributed Ledger Technologies (DLT), which consists of a ledger of transactions with multiple copies stored in a network of equals and competing peers, forming a distributed network (Bai and Sarkis 2020). Therefore, the expression blockchain technologies are used to describe a set of blockchain solutions from different manufacturers, such as Bitcoin, Ethereum, Hyperlegder Fabric, among others (Evans-Greenwood et al. 2016). These technologies can potentially reduce the technological uncertainties associated with industrial symbiosis networks (Ferreira et al. 2023a; Gonçalves et al. 2022). Blockchain technologies promote transparency, traceability, and security (Saberi et al. 2019), since they are based on a robust, distributed, and immutable ledger of transactions.

Additionally, these technologies can play a significant role within Industry 4.0, where the systems are expected to intensively use different technologies by digitising all processes within a trusted ecosystem (Cano-Marin et al. 2023; González-Tejero et al. 2023; Wang et al. 2022). According to Upadhyay et al. (2021), blockchain technologies can contribute to the circular economy, particularly considering the aspects of sustainability or social responsibility. Blockchain characteristics can help to reduce transaction costs, automate communications between relevant parties, and reduce a system's carbon footprint (Bai and Sarkis 2020). According to Boakye et al. (2022), in finance, blockchain could promote general banking services, improve current baking systems, encourage digital payments and financial auditing, and offer a substantial change in derivative transactions. Blockchain presents potential solutions to trust issues in trade finance, allowing the automation of transactions based on self-enforcing rules, making the whole process entirely secure and error-free (Difrancesco et al. 2023; Zhou et al. 2023; Sharma et al. 2023; Martinez et al. 2022). Furthermore, by ensuring that transactions occur in a mutually agreed manner, blockchain technology reduces the need to trust trading partners (Kowalski et al. 2021). Moreover, if we consider using a smart contract-enabled blockchain, specific features, such as human rights protection, can also be automatically enforced.

A consortium blockchain is ideal in an industrial symbiosis setting where all stakeholders must have approval and have a shared responsibility for the blockchain. Consortium blockchains are more decentralised than private blockchains, providing more security and lower operation and maintenance costs (Dib et al. 2018). A centralised administrator does not need to be involved in defining access control policies since the data owner should determine them and applied throughout the entire network (Wang et al. 2021; Chen et al. 2020). In this type of blockchain, pre-authorised nodes control the consensus process. Also, several entities can share responsibility for maintaining a blockchain, and pre-selected entities determine who can process transactions or access, i.e., the right to read the blockchain can be public or limited to specific participants (Liu et al. 2022). By using the consortium blockchain in industrial symbiosis networks, it is possible to track the source of raw materials, wastes, and by-products, the amount of energy used during production, the type of energy consumed throughout their life cycle, and the impact of the energy on the environment and resources (Shojaei et al. 2021). Most often, using by-products and waste resources frequently involves interactions between public and private entities, necessitating a concerted effort to ensure that the existing options and associated regulations are suitable for such purposes (Lybæk et al. 2021). A consortium blockchain blends public and private implementation elements, with a collective of participants achieving consensus. This approach ensures swift transaction execution while maintaining a decentralised governance structure (Creydt and Fischer 2019). As highlighted by Kouhizadeh et al. (2020), the objectives of Circular Economy can catalyse collaboration among consortium members within a blockchain platform. Figure 1 visually represents a smart contract between a hypothetical industrial unit participant, a prosumer, and two companies. It presents the network in the physical and digital domains. It also shows how both domains interact with each other through smart contracts.

A smart contract is merely a program stored on a blockchain that runs when a set of conditions is met. The usefulness for industrial activity and supply chain transactions is warranted since business rules can be transformed into computer programs using smart contracts (Dolgui et al. 2020). The importance of smart contracts in this context is due to the ability to make automated agreements, which are usually used to automate the execution of an agreement in which all parties are assured of the outcome instantly, without any intermediaries involved (Hewa et al. 2021).

Böckel et al. (2021) concluded that the connection between the areas of blockchain technology and the circular economy is still in a nascent stage, both in practice and research. Specifically, in the context of industrial symbiosis, few studies exist exploring the use of blockchain to promote an industrial symbiosis network. Ponis (2021) developed a business model to encourage industrial symbiosis

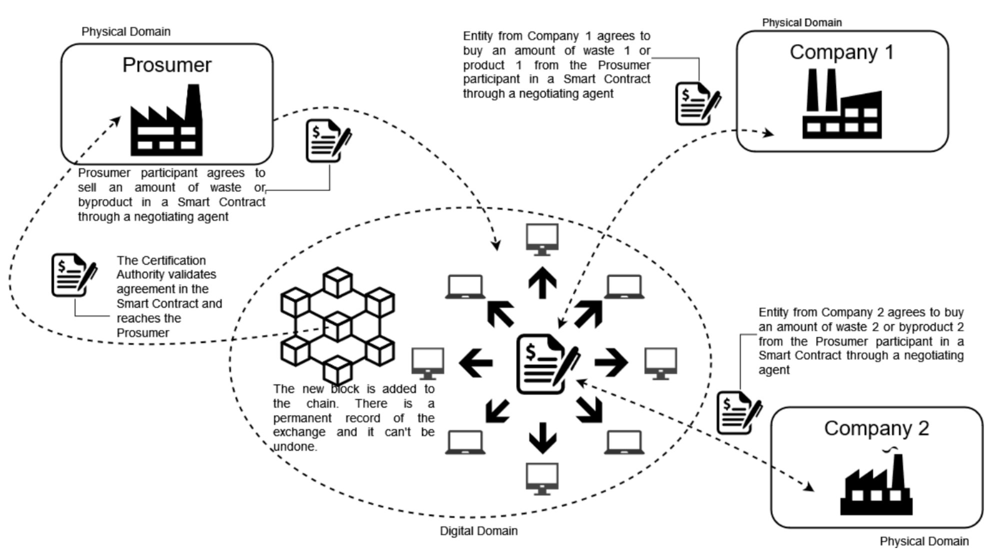


Fig. 1 Visual representation of a smart-contract formalisation between an industrial unit participant and prosumer and two companies

relationships supported by a blockchain-based marketplace that enabled the exchange of materials and by-products securely and reliably. Gonçalves et al. (2022) proposed a blockchain architecture design to enhance an industrial symbiosis network, providing the required transparency and trust. Thus, illustrating the potential of smart contracts to boost the development of industrial symbiosis networks. On the other hand, Bruel and Godina (2023) suggested using blockchain technology to digitise industrial symbiosis, making it more transparent and secure. Lastly, Liu et al. (2023) analysed the potential of digital twins for industrial symbiosis, promoting the use of digital twins for supply chain collaboration in industrial symbiosis.

1.3 Exploring blockchain technology in the additive symbiotic networks context

In the additive symbiotic networks context, Ferreira and Carvalho (2023) highlighted, in their review, that there is a research gap regarding the knowledge of how these symbiotic networks can be developed. The literature exploring the adoption of blockchain technology in this context is still very scarce. Ferreira et al. (2023a) identified a set of requirements for using blockchain technology in an additive symbiotic network context, highlighting the role of the technology as a supporting tool for implementing additive symbiotic networks. In another study, Ferreira et al. (2023b) explored the implications of blockchain technology adoption in an additive symbiotic network, proving that adopting the technology impacts the supply chain structure of an additive symbiotic network. Specifically in the power distribution between the stakeholders involved in the network. Even though the combination of additive manufacturing and blockchain technology might be particularly promising in the industrial symbiosis context and in an additive symbiotic network, as the literature shows, few studies have been developed exploring their mutual adoption, and the potential reciprocal implications between these two technologies remain unexplored (Ferreira et al. 2023a; Kurpjuweit et al. 2019). Moreover, only two studies highlighted the deployment of blockchain technology in an industrial symbiosis context (Bruel and Godina 2023; Gonçalves et al. 2022). Thus, this research intends to contribute to the existing research gap regarding the applicability of blockchain technologies in industrial symbiosis networks, specifically in an additive symbiotic network setting.

Using a case from a real additive manufacturing industry setting, this paper demonstrates the adoption of blockchain technology in the additive manufacturing context. It presents the requirements and an architecture of a blockchain network through smart contracts as an enabler of an additive symbiotic network. The case under analysis uses polyethene terephthalate (PET) bottles that appear in urban waste streams that, combined with the appropriate 3D printing technology, allow the production of recycled filament as material input for 3D printing equipment. This paper is structured as follows: after this introduction section, Sect. 2 presents the materials and methods used to carry out this research. Section 3 contains the main results and discussion around the proposed blockchain architecture. Finally, conclusions are highlighted in Sect. 4.

2 Methodology

Finding solutions that are adequate socially, environmentally, and economically to the problem of solid waste has become a rising concern for environmentalists, local governments, academics, and the overall community (Gutberlet 2012), especially in developing countries. The informal collection of valuable solid waste by waste pickers partially solves this problem. Around 1% of the world's urban population is involved in the process of valuable solid waste recovery; in Africa, Asia, and Latin America, the work of these people accounts for almost 30% of the valuable solid waste recovery process (Botello-Álvarez et al. 2018). Having a long tradition in human society, informal recycling is still prevalent in countries in the global South America. In Brazil, for example, similarly to other countries in the Global South, a significant part of the population is starting to live based on material recuperation through organised and informal cooperative recycling (Gutberlet 2012). Here, the waste pickers' activities are beginning to be established as urban cooperatives (Botello-Álvarez et al. 2018).

These cooperatives and other organisations, such as national recyclers or technology-related companies, can transform plastic waste streams into value-added 3D-printed products. Therefore, studying the development of additive symbiotic networks and finding tools that support the exchanges occurring within these networks is critical in this context.

The case study method is most suitable in early exploratory investigations, where the phenomenon is not entirely understood and there are still unknown variables. However, it can represent a detailed empirical description of the phenomenon itself using several sources of evidence (Yin 1994; Voss et al. 2002). Considering that this study is exploratory in its nature, the case study method was considered. Similarly to other authors, such as Ferreira et al. (2023a); Gonçalves et al. (2022), a single case study was conducted, as it allowed to gain a more in-depth understanding of the topics under study. A case study based on a real setting within the additive manufacturing industry was used to carry out this study. The selected case is related to post-consumer waste

– i.e., plastic bottles collected by waste pickers, which are later used to produce recycled filament to be incorporated into 3D printing equipment. This case constitutes an example of a real additive symbiotic network that aimed to use blockchain technology to concretise all the interactions between the stakeholders involved. Thus contributing to the still scarce literature around the use of blockchain technologies in additive symbiotic network contexts. Different blockchain technologies can be deployed in an additive symbiotic network; hence, the aim is not to generalise the results. Instead, this single case study, similar to Ferreira et al. (2022a) and Naghshineh and Carvalho (2022), is used as a pilot case to act as a base for future research considering multiple case studies, and like this, is regarded as an essential contribution to knowledge (Yin 2014). Specifically, blockchain's applicability in additive symbiotic networks proves that this technology supports their development.

The development of the case study was conducted in two phases: phase (i) map and characterise the additive symbiotic network under study (a similar methodology to Ferreira et al. (2023b) was used) and phase (ii) proposal of a blockchain-based architecture to support the symbiotic network (a similar approach to Gonçalves et al. (2022) was followed).

In phase i), primary data was collected through structured and unstructured interviews with one expert from one of the stakeholders involved in the additive symbiotic network under study to map and characterise the network. The expert represented the network's focal organisation and knew about all the exchanges and stakeholders involved. The expert was a technical advisor to the leadership team with over 15 years of experience and belonged to B-PET, a 3D printing equipment and services company located in Buenos Aires, Argentina.

Within this study's case, waste pickers from a local cooperative in Argentina, Cooperative Correcaminos, collect post-consumer PET (PCR PET) bottles from urban waste collection activities. The local cooperatives transform these post-consumer PET waste streams into bales and sell them to one of Argentina's recyclers – ALPEK. In exchange, ALPEK sells PET pellets or flakes prepared to be incorporated in 3D printers to local cooperatives. Simultaneously, B-PET (a technological company that sells additive manufacturing technologies and services) sells 3D printing technology and services to local cooperatives, allowing them to use PET pellets or flakes to produce recycled filament for 3D printers. A funder is needed to help the local cooperatives acquire funds to invest in 3D printers and related technology. Finally, after producing the recycled filament, local cooperatives can make customised products using their own 3D printers or sell them to customers, such as prosumers or schools. Figure 2 represents the additive symbiotic network considering the different stakeholders and their interactions (named "flows").

The interactions between the stakeholders of the additive symbiotic network under study are described in detail in Table 1.

Phase ii) of the case study's development corresponds to the proposed blockchain solution to enable the additive symbiotic network described, which will be detailed in the next

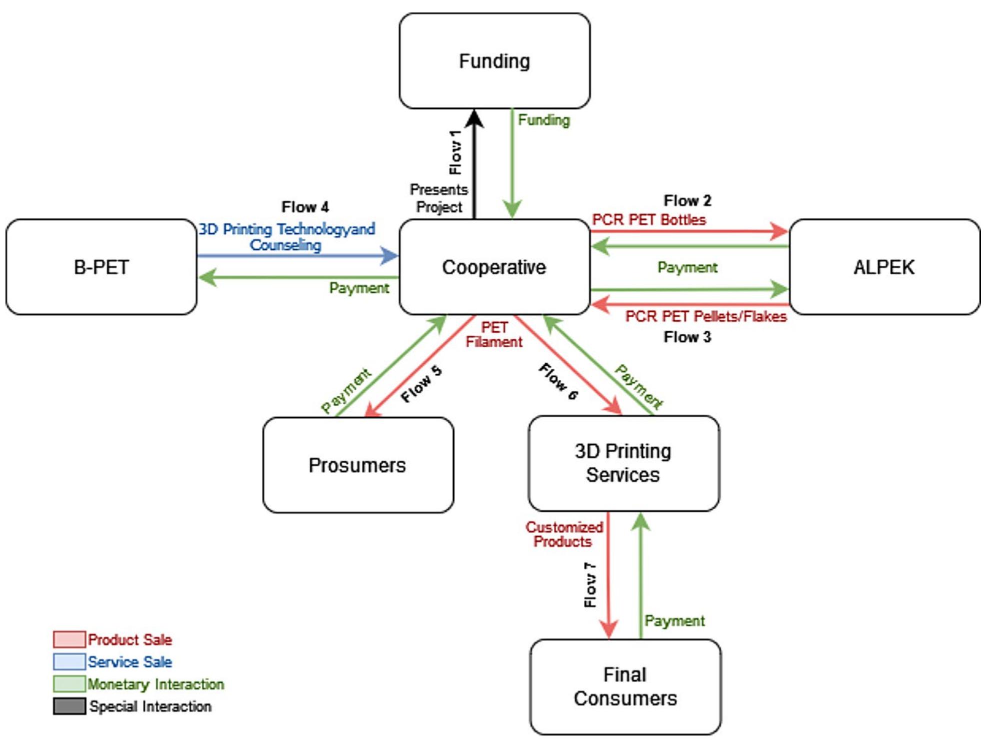


Fig. 2 Additive symbiotic network from B-PET's case study

Table 1 Description of the flows between the stakeholders in the additive symbiotic network under study

Flow number	Description
1	The local cooperative needs to invest in appropriate 3D printing technology and equipment; thus, a funder is needed. The local cooperative presents its project, along with a funding request. Once funding entities have evaluated the project, funds may be made available (if they like it).
2	After collecting post-consumer PET (PCR PET) bottles from urban waste streams, the local cooperative sends the collected bales of PCR PET bottles to ALPEK (one of Argentina's certified recyclers), which converts them into PET pellets or flakes. In return, ALPEK pays the local cooperative.
3	The local cooperative sends monetary aid to ALPEK to convert the waste (bales of PCR PET bottles) into PET pellets or flakes. Once this process is complete, the result (PET pellets or flakes) is returned to the local cooperative.
4	B-PET offers the local cooperative 3D printing technology and consulting services necessary to use PET pellets or flakes to produce recycled filament for 3D printers. In return, the local cooperative pays B-PET a fee.
5	The local cooperative can produce recycled filament from PET pellets or flakes. They can use this filament for their own purposes and projects or sell it to customers. The customers, in exchange for the product, offer payment.
6	The local cooperative can also sell recycled filament to 3D printing services companies, which in return offer a monetary value.
7	The 3D printing services with recycled filament can engineer customised products and produce them for their customers, who pay for the products a monetary value.

Table 2 Required data sent to the additive symbiotic network entailed in the sell orders of the proposed blockchain architecture

Variables	Required data sent to the additive symbiotic network for sell orders
id	The unique ID used to reference the sell order (used to create buy orders)
amount	The amount of the product (or service) available for sale
price value	The amount of monetary value that the whole amount of product will cost
price exponent	The decision of the decimal cases the amount has
price currency	The type of currency to be used (EUR, USD, GBP, …)
type	The type of order: SELL or BUY. In this case, it is SELL.
organisation id	The unique ID of the organisation selling the product (or service)
product id	The unique ID of the product
unit id	The type of unit chosen (KG, LBS, …)

Table 3 Required data sent to the additive symbiotic network entailed in the buy orders of the proposed blockchain architecture

Variables	Required data sent to the additive symbiotic network for buy orders
id	The unique ID used to reference the buy order (needed for the transaction to be viewable)
amount	The amount of the product (or service) that is being bought
organisation id	The unique ID of the organisation buying the product (or service)
order id	The unique ID that references the sell order of what the user is buying

section. In this solution, data processing is done transparently using smart contracts. These smart contracts are available in the online appendix at DOI: https://doi.org/10.5281/zenodo.6941231. However, it is essential to note that this solution is still in the *proof-of-concept* stage, to be further tested in the future.

In the proposed solution, the red-coloured (product sale) or blue-coloured (service sale) exchanges presented in Fig. 2 are recognised as sell orders. The entity desiring to sell a product creates a listing to sell that specific product or service. The data sent to the network entailed in these sell orders is presented in Table 2.

The green-coloured (monetary interaction) exchanges in Fig. 2 are recognised as buy orders. The entity creates a listing to buy a specific product or service. Table 3 presents the data sent to the network entailed in these buy orders.

3 Results and discussion

This section presents the requirements and details regarding the proposed blockchain architecture for the additive symbiotic network under study.

3.1 Requirements and Blockchain Technology Selection

Technical requirements must be considered to adopt blockchain technology effectively in the additive symbiotic network under study. The system needs to accept new nodes into the network without downtime or setup, process transactions between the additive symbiotic network, and create and list products as well as orders (i.e., buy" or "sell" type that can be in "open" or "closed" state). The system should also prevent unauthorised personnel from accessing the data; in other words, it should be confidential.

Hunhevicz and Hall (2020) proposed a framework to help decide whether a DLT is better suited (over a traditional database) for a project and also which type of DLT would be best. This framework is split into three stages, each one having multiple questions. The first stage determines if a DLT is necessary for the project. The second stage focuses on selecting the best DLT design for the project. The third and final stage is focused on the constraints of the project, which may influence the results of the previous stages depending on how much importance is put into one constraint. For example, the constraint of throughput, ensuring that the system can process a certain minimum number of requests simultaneously at all times, may be of greater importance in some cases and lower in others.

For the case under study, in regards to the first stage of Hunhevicz and Hall's (2020) framework, the usage of a traditional database would not be possible since there would be a requirement for these transactions to be tracked and, as a whole, the integrity must be guaranteed. There are also multiple writers or stakeholders who have the power to update the ledger. There is no interest in using a Trusted Third Party since that would imply another organisation outside the network to access the data. Though stakeholders do not know each other, the system knows who each stakeholder is. Furthermore, the stakeholders' interests are also not aligned since they exchange different resources among themselves, thus affecting the power distribution in the network (i.e., stakeholders hold more power in the network than others). Concerning the second phase, public verifiability is not desired as organisations might share sensitive and private information, and there is a requirement to impose control at the protocol level. Considering all these points, according to Hunhevicz and Hall (2020), a Private Permissioned DLT is the better choice for the case under study.

3.2 Proposed Architecture

The chosen DLT is Hyperledger Fabric, and the smart contracts are written in the Go programming language. Smart contracts allow industrial symbiosis participants to define their relationships within the system and how they interact. They also establish industrial symbiosis control and process procedures, such as participant certifications and approvals. Currently, these are run through a Command-Line Interface, such as Linux's bash.

This DLT features Peer and Orderer nodes. The Peer node is responsible for hosting the ledger and chain code. It is not wrong to call these the foundation of a blockchain network. Among these types of nodes exist: Commitment peers focused entirely on storing the ledger and Endorsement peers, which can also run chaincode, allowing these nodes to run smart contracts. These nodes can do two types of requests - queries or updates. Queries are evaluations of transactions that will not write anything to the ledger, and all information required to complete them should be available in the peer's local ledger. As such, the return is immediate, and there is no need for contact with other nodes. However, update requests (invoke) require approval from other peers to be completed (known as consensus). In this case, the transaction is sent to the Orderer node. In the case of the network under study, all its stakeholders (Cooperative Correcaminos, ALPEK, B-PET, Prosumers, 3D Printing Services, and Funding Users) will run Peer nodes. As for Orderer nodes, the entity responsible for hosting is Cooperative Correcaminos.

The Orderer node controls channel access, ensuring only those with the proper permissions can read and write data. Channels are private subsections of the network that allow for two or more specific network members to exchange transactions confidentially. The Orderer node is also responsible for the transaction order, split into three phases (Fig. 3).

In the first phase, a client sends a proposed ledger change to a trusted peer (Endorsement peer), which executes the proposed transaction and returns an endorsed transaction to the client. Then, in the second phase, the endorsed transaction is forwarded to the Orderer, which packages it into a block alongside other endorsed transactions. After this block is created, it is distributed and communicated to all peers on the channel. Finally, in the third phase, each peer will validate every transaction and confirm that the ledger remains valid with the block in question. If the process is still valid by the end, the block gets added to the ledger.

All data is stored in five different data structures, as represented in the Entity Relationship Diagram (Fig. 4), namely:

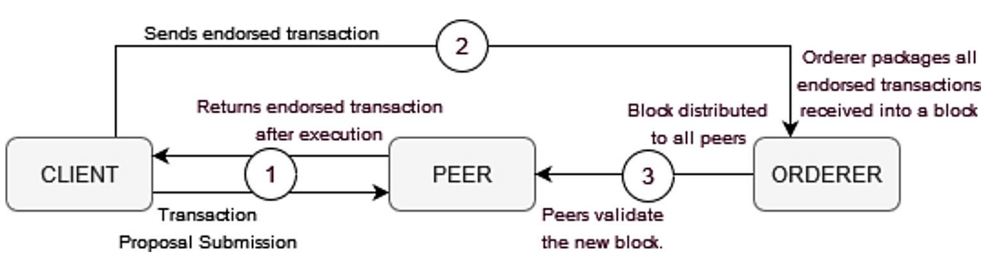


Fig. 3 How new blocks are added to the ledger

- Organisation structure stores each organisation's name, address, and phone. Each organisation has a unique ID and represents a different entity;
- Unit structure, which represents the proper metric of measurement to use, stores a name and description as well as an ID;
- Product structure, which represents the product, stores a name and description and has a unique ID;
- Order structure is responsible for storing all data related to selling or buying product requests. Each order has a unique ID and stores the amount being sold or purchased, the price of it (which includes the total value as well as the currency), the type of order (if it is a request to sell or buy), and the status of the order (if it is still available or if it has already been completed);
- A transaction structure is created when an organisation buys or sells a product from another organisation's order. It stores the amount purchased and the transaction status (e.g., whether it is open, closed, cancelled, waiting for payment, paid, delivering, etc.). It also stores a unique ID for each transaction.
- Request structure created by the system moderator (a member of Cooperative Correcaminos) to request project funding. It stores a unique ID, description of the project, and status of the request.
- Offer structure is created when a funding-related user is willing to offer funding towards the proposed project. A unique ID, the amount provided, and the organisation's and request's IDs are stored.

The proposed solution uses Hyperledger Fabric Attribute-Based Access Control to manage what users can do in the network by adding attributes to each user's certificate. For example, if a user wants to create a new order, they must have the attribute "order.create" in their certificate. Every user in the network is required to have their own certificate. Of the available databases in Hyperledger Fabric, CouchDB was the one chosen. As for the ordering service, Raft is being used since it is recommended in Hyperledger's documentation.

The Case Use Diagram, presented in Fig. 5, describes what each member of each organisation involved in the network can do in the system.

In the additive symbiotic network under study, the founder, represented by the Cooperative Correcaminos, is responsible for managing organisations in the system and

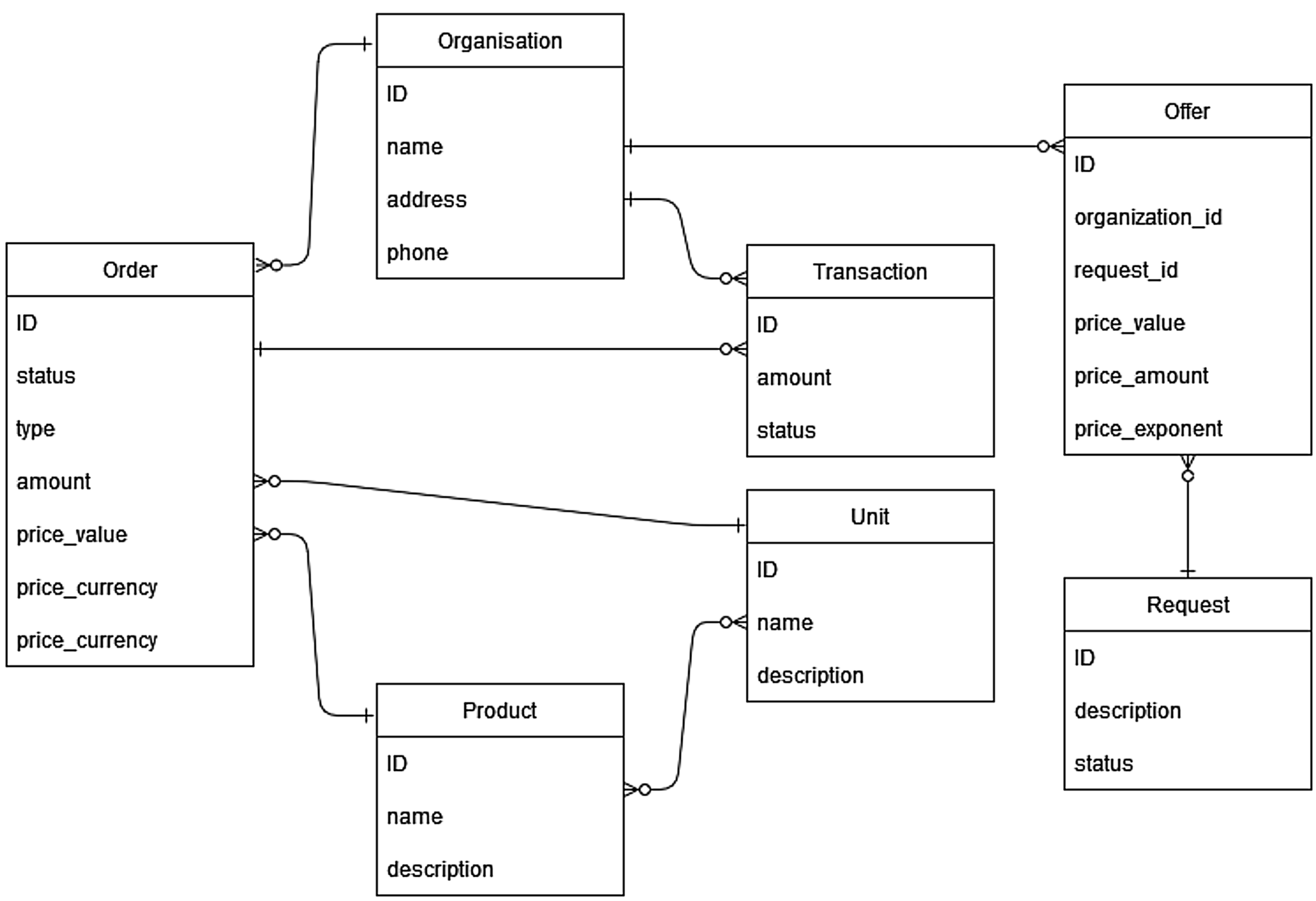


Fig. 4 Entity Relationship Diagram

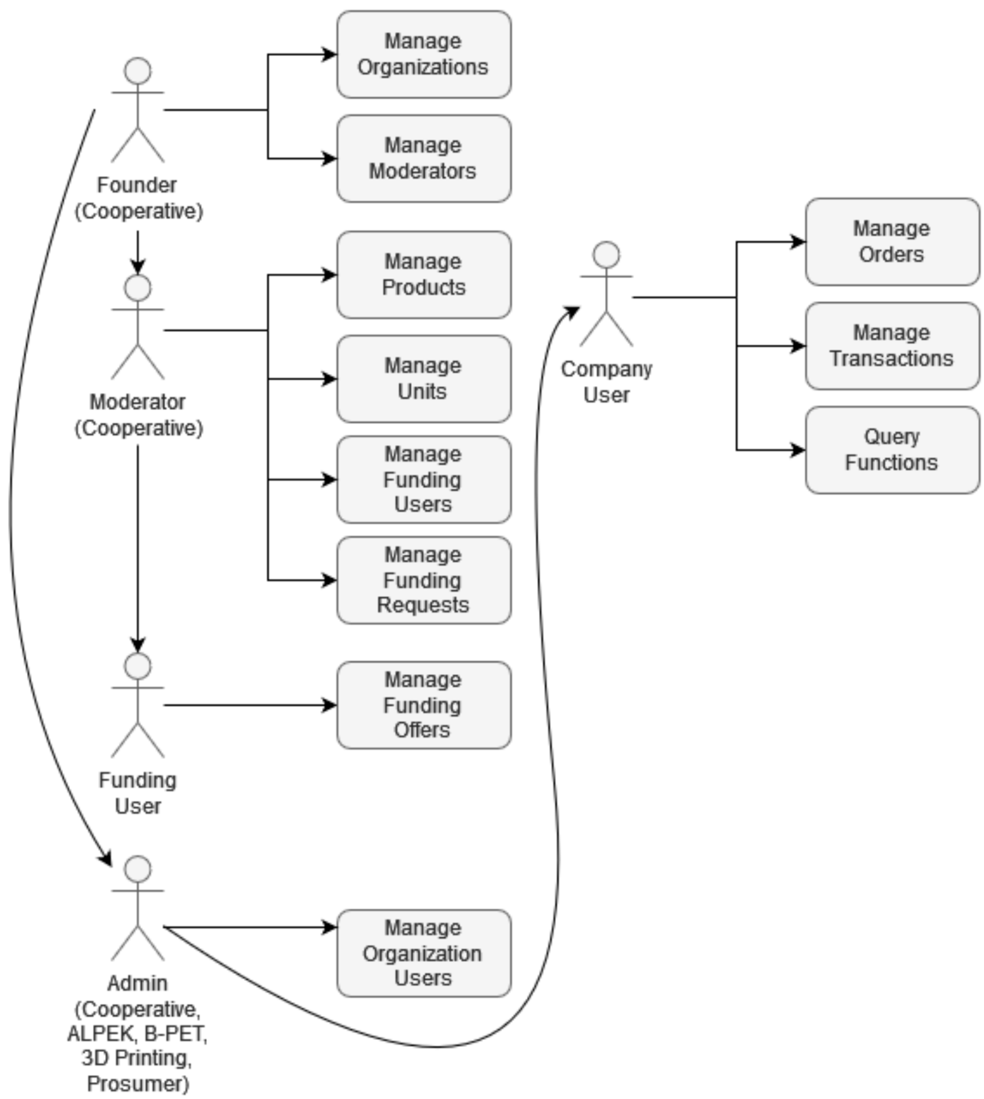
can add new ones or edit/delete existing ones. The founder role is also responsible for giving the moderator role to another user. The moderator, which also corresponds to the Cooperative Correcaminos within this case study, is responsible for adding products/units to the system. For example, if B-PET wants to provide a new type of service, it first needs to contact a moderator with information about the service offered. A moderator adds the new service to the system, and only then can B-PET create a new order to sell that service. The moderator can also generate funding requests, which present a project to users from various organisations capable of providing monetary support. Funding-related users can access a list of funding requests within the system and create offers with a monetary value of their own choosing.

The founder is also responsible for giving the administrator role to a member of each organisation within the network. This administrator member is responsible for attributing the "Company User" role to other members within its own organisation. The "Company User" role represents the entity responsible for creating orders to buy/sell, creating transactions, and any query functions (functions responsible for listing data). Within this case study's network, most of the stakeholders that participate in it and are involved in the transactions will have "Company User" roles – these correspond to the stakeholders Cooperative Correcaminos, ALPEK, B-PET, the Prosumers, and the 3D printing services companies. Users of the remaining stakeholders dedicated to funding will have a different role – "Funding User".

Figure 6 represents the proposed blockchain architecture solution for the additive symbiotic network under study.

There are only four Certification Authorities (CA): one for the founder peer and orderer node, another for the moderators, and finally, each organisation also gets a CA, which is used to add users to the system ("CompanyUser" role). All of these nodes communicate with each other through a single transaction channel. As such, all transactions in the system are transparent to the stakeholders while not being visible to anyone outside the system.

Fig. 5 Case Use Diagram



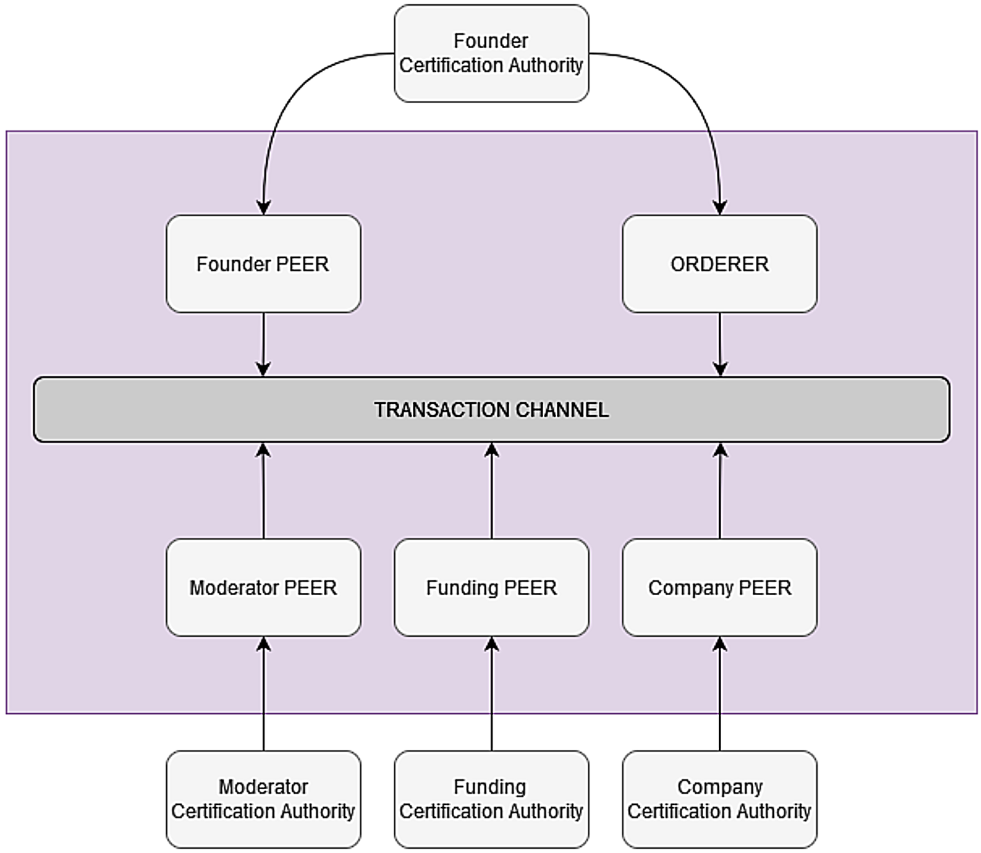


Fig. 6 Proposed blockchain architecture solution for the additive symbiotic network under study

An example is given to demonstrate the necessary steps to occur for a transaction to be successfully completed. This example focuses on the flow that represents the exchange of PET pellets from ALPEK to the cooperative in exchange for money (corresponding to Flow 3 from Fig. 2). Thus, the Cooperative Correcaminos organisation wants to buy PCR PET pellets from the ALPEK organisation.

Firstly, ALPEK (attempting to sell a product - in this case, the PCR PET pellets) must make an order to sell. To do that, they must verify the ID of the product they want to sell, which can be done with the following command, which returns all products in the ledger:

```
$ peer chaincode query -C mychannel -n abac -c ‘{“Args” :[ “GetAllProducts”]}’

[{"id":"PCRPET-pellets","name":"PCRPET-Pellets","description":"Plastic
Pellets","units":[{"id":"kg","name":"Kilos","description":"Kilos"}]}]
```

If the product they wish to sell is unavailable, they would have to contact an entity with higher permissions, a moderator (in this case, the Cooperative Correcaminos), to add that type of product to the system. For example, if ALPEK wants to sell 2000 kilos of PCR PET pellets for a total of 1000 EUR, they would run the following command to create a new order to sell with the unique ID “order1”:

```
$ peer chaincode invoke "${OPTIONS[@]}" -C mychannel -n abac -c
‘{"function":"CreateOrder" ,"Args":["order1", "2000", "1000", "2", "EUR", "SELL",
"ALPEK", "PCRPET-pellets", "kg"]}’

[chaincodeCmd] chaincodeInvokeOrQuery -> INFO 001 Chaincode invoke successful.
result: status:200
```

With the new order to sell created successfully, the cooperative can buy the product that ALPEK is selling. This is done by confirming the order ID through a command similar to the first one - instead of "GetAllProducts", "GetAllOrders" is used. This will return a list of all orders in the ledger.

With the order's ID, the cooperative can run the following command to create a transaction and buy what ALPEK sells. In this case, the cooperative is buying 500 kilos of the total 2000 kilos for sale. This transaction gets the unique ID "transaction1".

```
$ peer chaincode query -C mychannel -n abac -c
'{"Args":["GetAllTransactionsForOrder", "order1"]}'

[{"id":"transaction1","amount":500,"description":"","status":"OPEN","organization_id
":"COOPERATIVE","order_id":"order1"}]
```

If a member of the system wants to verify information regarding transactions for the order created by ALPEK, the only thing required is to make a query request, calling the function "GetTransactionsOrder" with the ID of the order (in this case, "order1"):

```
$ peer chaincode invoke "${OPTIONS[@]}" -C mychannel -n abac -c
'{"function":"MakeTransaction" ,"Args":["transaction1", "500", "COOPERATIVE",
"order1"]}'

[chaincodeCmd] chaincodeInvokeOrQuery -> INFO 001 Chaincode invoke successful.
result: status:200
```

3.3 Discussion and research implications

3.3.1 Discussion of results

This research highlights how blockchain technology can be applied to an additive symbiotic network. Through the development of the case under study, in a first stage, it was possible to infer the requirements to be considered when developing a blockchain architecture for an additive symbiotic network. These are: integrity needs to be guaranteed, there are multiple writers in the network, there is no need for using a Trusted Third Party, the system knows who each participant is, participants' interests are not aligned, public verifiability is not desired, and there is a need to impose control at the protocol level. Considering these and the additive symbiotic network under study, a blockchain architecture was developed in a second stage. The proposed solution employs the Hyperledger Fabric Attribute-Based Access Control, which allows the management of what users can do in the network and features Peer and Orderer nodes. In this blockchain architecture, only four Certification Authorities exist, and the nodes communicate with each other through a single transaction channel. Using smart contracts, the proposed solution allows industrial symbiosis participants to define their relationships within the system and how they interact with one another.

Even though the literature is still very scarce on these topics, this study allows to retrieve some general conclusions about deploying blockchain technologies in an additive symbiotic network context. Through the exploratory case study that was carried out, the proposed blockchain solution, as demonstrated beforehand in sub-Sect. 3.2, presents several advantages when compared to traditional data storage technologies. It allows the elimination of intermediary entities, as there is no longer a need for a third party to be involved in the transactions within the network, and the transactions run quicker and smoothly since there is no requirement to wait for responses. This advantage is highlighted by Kouhizadeh and Sarkis's (2018), who proposed a blockchain approach for greening supply chains. Even though the architecture of Kouhizadeh and Sarkis's (2018) study follows different flows from the current study, the ability to track information and communicate without needing an intermediary is seen as an important advantage of blockchain technology. Moreover, using smart contracts saves time and reduces costs since the contract terms are agreed upon and set between additive symbiotic stakeholders. A third party does not have to verify them. Thus, the whole process takes less time. This advantage is also corroborated by Ponis (2021), that highlighted the marginal costs of developing a new contract or replacing one with an improved version are expected to be lower with blockchain, and all the exchanges (i.e., transactions between the stakeholders) are self-executed and the transmission of ownership, value, information and products takes place autonomously. Additionally, the transaction transparency offered by blockchain reduces friction and infraction within the symbiotic network, as the records of each transaction cannot be changed at any point. Blockchain improves the security of records; thus, each transaction among the stakeholders is permanently recorded on the blockchain and made available to the stakeholders with proper permission. These findings are corroborated by Gonçalves et al. (2022), who suggested a blockchain architecture design to enhance an industrial symbiosis network within the Pulp, Paper and Cardboard sector.

Another advantage of using blockchain in an additive symbiotic context is that the integration into the system is also much more straightforward since trust is not required to be built between all entities. Blockchain helps to improve trust among the symbiotic stakeholders, supporting cooperation and trust mechanisms between them. Indeed, in their study, after verifying that blockchain technology fulfils the requirements to be adopted in additive symbiotic networks, Ferreira et al. (2023a) have concluded that this innovative technology can improve trust imbalances between symbiotic stakeholders. Furthermore, these findings are also corroborated by Bruel and Godina (2023) and by Ponis (2021), who went into detail on blockchain technology applied to industrial symbiosis through smart contracts and highlighted the role of the technology in improving trust between the symbiotic stakeholders. Kouhizadeh and Sarkis (2018) have also considered using smart contracts in their study and mentioned the possibility of using cryptocurrency because it is considered more secure.

Moreover, in an additive symbiotic network context, blockchain allows keeping available a tracking record of the resources (products and wastes) exchanged - namely, origin and details, especially in cases of the source of wastes comprising AM filaments. This advantage has also been emphasised by Bruel and Godina (2023) in the industrial symbiosis context and by Ferreira et al. (2023a) in the additive symbiotic context, most AM processes are sensitive to the input material characteristics, so it is critical to trace the origin of wastes and residue flows. Blockchain facilitates collaboration, as all blockchain technologies are collaborative in nature, supporting the exchange of resources between the additive symbiotic stakeholders. The platform availability allows businesses to be conducted at any time, considering that in additive symbiotic networks, sometimes the stakeholders involved may be geographically distant from each other.

Despite all the above advantages, adopting such innovative technology as blockchain in an additive symbiotic network context poses several challenges. One main challenge identified in this research relates to the complexity associated with introducing a novel technology, such as blockchain technology, in an emerging industry, such as the additive manufacturing industry, which requires training staff or acquiring new IT infrastructures. This challenge is also highlighted by Bruel and Godina (2023) as a barrier that may interfere with implementing blockchain technologies in industrial symbiosis networks due to the lack of IT infrastructures to host the system and technical know-how to operate blockchain technologies. Furthermore, Ferreira et al. (2023a) have also emphasised the same challenge when studying the technological implications of blockchain technology in an additive symbiotic network.

Another challenge of adopting this disruptive technology in such an additive symbiotic context is the technology immaturity of blockchain when compared to other data storage technologies, such as database servers. These remarks are emphasised by Bruel and Godina (2023), who concluded that the immaturity of blockchain technologies and lack of rewards and incentives to promote blockchain technologies are some of the main barriers to adopting blockchain technology in an industrial symbiosis context. Although most of the advantages obtained by the adoption of blockchain technologies are applicable in a broader context, like the circular economy (Basile et al. 2023) and the additive manufacturing context (Piscicelli 2023; Nandi et al. 2021), which includes industrial symbiosis networks (Bruel and Godina 2023; Gonçalves et al. 2022; Ponis 2021), this study proves that these advantages are also extended to the context of additive symbiotic networks. Thus contributing to the existing research gap regarding the applicability of blockchain technologies in an additive symbiotic network setting and contributing to ensuring a sustainable use of technologies and enabling the implementation of systems and infrastructures to support the development of additive symbiotic networks (González-Tejero et al. 2023).

3.3.2 Theoretical contributions

This research highlights how blockchain technology can be applied to an additive symbiotic network. Even though the literature is still very scarce on these topics, this study allows to retrieve some general conclusions about deploying blockchain technologies in an additive symbiotic network context. Through the exploratory case study that was carried out, the proposed blockchain solution, as demonstrated beforehand in sub-Sect. 3.2, presents several advantages when compared to traditional data storage technologies. It eliminates intermediary entities, as there is no longer a need for a third party to be involved in the transactions within the network, and the transactions run quicker and smother since there is no requirement to wait for responses. This advantage is highlighted by Kouhizadeh and Sarkis (2018), who proposed a blockchain approach for greening supply chains. Even though the architecture of Kouhizadeh and Sarkis's (2018) study follows different flows from the current study, the ability to track information and communicate without needing an intermediary is seen as an important advantage of blockchain technology.

Moreover, the use of smart contracts allows for saving time and reducing costs since the contract terms are agreed upon and set between additive symbiotic stakeholders, and a third party does not have to verify them. Thus, the whole process takes less time. This advantage is also corroborated by Ponis (2021), who highlighted that the marginal costs of developing a new contract or replacing one with an improved version are expected to be lower with blockchain, and all the exchanges (i.e., transactions between the stakeholders) are self-executed. The transmission of ownership, value, information and products takes place autonomously. Additionally, the transaction transparency offered by blockchain reduces friction and infraction within the symbiotic network, as the records of each transaction cannot be changed at any point. Blockchain improves the security of records; thus, each transaction among the stakeholders is permanently recorded on the blockchain and made available to the stakeholders with proper permission. These findings are corroborated by Gonçalves et al. (2022), who suggested a blockchain architecture design to enhance an industrial symbiosis network within the Pulp, Paper and Cardboard sector.

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3.3.3 Practical contributions

Despite all the above advantages, adopting such innovative technology as blockchain in an additive symbiotic network context poses several challenges. One main challenge identified in this research relates to the complexity associated with introducing a novel technology, such as blockchain technology, in an emerging industry, such as the additive manufacturing industry, which requires training staff or acquiring new IT infrastructures. This challenge is also highlighted by Bruel and Godina (2023) as a barrier that may interfere with implementing blockchain technologies in industrial symbiosis networks due to the lack of IT infrastructures to host the system and technical know-how to operate blockchain technologies. Furthermore, Ferreira et al. (2023a) have also emphasised the same challenge when studying the technological implications of blockchain technology in an additive symbiotic network.

Another challenge of adopting this disruptive technology in such an additive symbiotic context is the technology immaturity of blockchain when compared to other data storage technologies, such as database servers. These remarks are emphasised by Bruel and Godina (2023), who concluded that the immaturity of blockchain technologies and the lack of rewards and incentives to promote blockchain technologies are some of the main barriers to adopting blockchain technology in an industrial symbiosis context. Although most of the advantages obtained by the adoption of blockchain technologies are applicable in a broader context, like the circular economy (Basile et al. 2023) and the additive manufacturing context (Piscicelli 2023; Nandi et al.

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4 Conclusions

Industry 4.0 technologies, such as blockchain technology and additive manufacturing, can support organisations towards sustainable objectives and engage in circular business models, encouraging the development of industrial symbiosis relationships and promoting additive symbiotic networks. Despite the clear benefits of adopting blockchain technology in industrial symbiosis settings, there is a lack of research exploring the adoption of blockchain in an additive symbiotic network, and the literature relating these two topics is still scarce.

In this research, an architecture of a blockchain network using smart contracts is proposed to enable an additive symbiotic network. An illustrative case study was developed in two phases to carry out the research – phase (i) mapped the additive symbiotic network under study, and phase (ii) proposed a blockchain-based architecture to support the network. The case study is based on a real setting and represents an additive symbiotic network in which plastic bottles from urban waste are collected and transformed into pellets to produce recycled filament for 3D printers.

The development of the case study reflects the requirements and details that must be considered when developing the proposed blockchain architecture. For the specific network under study, these requirements included: (i) integrity needs to be guaranteed, (ii) there are multiple writers in the network, (iii) there is no need for using a Trusted Third Party, (iv) the system knows who each participant is and (v) participants' interests are not aligned. These requirements have already been recognised in the literature by Ferreira et al. (2023a) as the main requirements for using blockchain technology in an additive symbiotic network context. Furthermore, this research identified additional requirements to use the technology in such symbiotic settings, namely: (i) public verifiability is not desired, and (ii) there is a need to impose control at the protocol level. Considering these requirements, the proposed solution employs the Hyperledger Fabric Attribute-Based Access Control. Similarly to Bruel and I Godina (2023) and Gonçalves et al. (2022), the private architecture seemed to be the better choice for the current case study.

The potential for blockchain technology to maintain and foster additive symbiotic networks in different contexts and countries is still in its infancy, with barely any recorded practical application yet (Ferreira et al. 2023b). This research intended to foster knowledge around adopting innovative tools, such as blockchain technology, to enhance the development of additive symbiotic networks. The current research demonstrated the potential of blockchain technology to be adapted to resources that have a specific value and are processed through several intermediaries, particularly in organised networks of industrial synergies, where traceability becomes increasingly challenging. Moreover, even though the advantages of adopting blockchain technologies have started to be emphasised in the literature around circular economy and the additive manufacturing context (Nandi et al. 2021; Piscicelli 2023) and in industrial symbiosis networks (Bruel and Godina 2023; Gonçalves et al. 2022), in additive symbiotic contexts, these advantages remain unexplored. This research extended the benefits highlighted in the literature to the additive symbiotic context. These advantages include eliminating intermediary entities, ensuring secure tracking records of resources' origin and details, improving transaction transparency and platform availability to conducted businesses at any time, and easing collaboration. Despite these advantages, adopting such disruptive technology in an additive symbiotic network context poses challenges highlighted in this research, such as the need for training staff or acquiring new IT infrastructures and the technological immaturity of blockchain technologies compared to other traditional databases. These findings are corroborated by Bruel and Godina (2023) for an industrial symbiosis context.

There are several limitations concerning this research. Even though the proposed blockchain architecture for an additive symbiotic network is based on the case study's specific context, the solution can be adapted to other contexts with the required changes (by adding or eliminating flows, stakeholders, and products or creating and altering smart contracts terms). The data management in an industrial symbiosis business model through the proposed blockchain architecture has its own specificities due to the potential involvement of trusted third parties for information verification and contract certification, among others. Yet, the proposed blockchain architecture can be adapted to fit in a supply network producing secondary materials. Moreover, another limitation concerning this research, is that the current system requires the payment to happen outside of the network. The system only creates a record that this exchange has happened. Thus, implementing cryptocurrency could be a way to quicken transactions further, removing the necessity for payments to occur outside of the network and making these processes more transparent since the record of the payment going through will be available to be consulted. Future research in implementing cryptocurrency to enhance an additive symbiotic network is needed.

The first experiments in various blockchain applications need vital funding, which could yield remarkable benefits. Also, there are no existing regulations for blockchain technology, and as it rapidly develops, a gap is becoming apparent between the current legislation and the implications it could have on additive symbiotic networks. Future studies could focus on a practical application of additive symbiotic networks, initially with few participants. Other studies can be made by addressing the widening gap between the lack of legislation and the rapid development of IT infrastructures based on blockchain technology. As a result of blockchain technology applied to additive symbiotic networks, there are many future potential applications, such as increasing the complexity of the networks, developing more multifaceted pricing models, adding more commodities, trying new business models, and including new types of participants and/or prosumers.

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