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Boosting additive circular economy ecosystems using blockchain: An exploratory case study

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ABSTRACT

The role of new technologies such as additive manufacturing and blockchain technology in designing and implementing circular economy ecosystems is not a trivial issue. This study aimed to understand if blockchain technology can be an enabler tool for developing additive symbiotic networks. A real case study was developed regarding a circular economy ecosystem in which a fused granular fabrication 3D printer is used to valorize polycarbonate waste. The industrial symbiosis network comprised four stakeholders: a manufacturing company that produces polycarbonate waste, a municipality service responsible for the city waste management, a start-up holding the 3D printer, and a non-profit store. It was identified a set of six requirements to adopt the blockchain technology in an additive symbiotic network, bearing in mind the need to have a database to keep track of the properties of the input material for the 3D printer during the exchanges, in addition to the inexistence of mechanisms of trust or cooperation between well-established industries and the additive manufacturing industry. The findings suggested a permissioned blockchain to support the implementation of the additive symbiotic network, namely, to enable the physical transactions (quantity and quality of waste material PC sheets) and monitoring and reporting (additive manufacturing technology knowledge and final product's quantity and price).

Future research venues include developing blockchain-based systems that enhance the development of additive symbiotic networks.

1. Introduction

Industrial symbiosis has emerged as a strategy to put into practice circular economy ecosystems. It can be considered a mutually beneficial relationship among different industries within a collective approach, aiming to achieve competitive advantages through exchanging materials, energy, water, and by-products (Chertow, 2000; Chopra & Khanna, 2014). This exchange of resources between different entities such as manufacturing companies, social enterprises, and even research centres and regulators creates an Industrial Symbiosis Network (ISN). Like in any other peer-to-peer context of services and marketplaces, trust plays a critical role in developing relationships and interactions (Hawlitschek et al., 2018; Ponis, 2021). Thus, there is a need to implement new technologies that enable the ISN's requirements concerning trust between the stakeholders and the exchange of resources.

The umbrella of Industry 4.0 technologies (Dalenogare et al., 2018; Vaidya et al., 2018) is expected to boost the implementation of circular economy ecosystems (Maranesi & De Giovanni, 2020). Companies can use those technologies to generate, trace, and analyze large amounts of data in real-time, improve the operational and strategic decision-making processes, and support flexible manufacturing processes (Dalenogare et al., 2018). Blockchain technology, for example, is seen as typical technology that may contribute to companies implementing circular supply chains assuring information reliability, traceability and transparency (Maranesi & De Giovanni, 2020). Furthermore, the additive manufacturing (AM) technology has also become a source of product and process innovation (Yuan et al., 2022), enabling customized products and providing new opportunities to create value in an ISN setting (Ferreira et al., 2021). Projects such as RecWoo3D (aclima, 2018) and The Fenix Project (Rosa & Terzi, 2021) demonstrate how AM technology

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can use recycled materials as material inputs for AM processes. Likewise, already established companies such as OWA 3D (OWA, 2021) show how AM technology can create opportunities to develop circular economy ecosystems by producing a polystyrene filament using old cartridges.

In their literature review, Ferreira et al. (2021) provided valuable insights on how AM can be used to promote waste valorization within ISNs. AM technologies possess unique characteristics that support circular economy strategies such as: encouraging repair and refurbishment operations, extending the products lifecycle by printing the necessary parts on site and the potential waste reduction and material-input savings (Hettiarachchi et al.2022). This paper extends the use of AM technologies in circular economy ecosystems and names them “additive circular ecosystems”. The additive circular ecosystems can be supported by ISNs using AM technology to improve the circularity of materials; In this paper, these symbiotic networks are designated “additive symbiotic networks”. The successful adoption of AM technologies introduces challenges due to their digital nature, such as a verifiable source of production, quality issues, intellectual property questions, adherence to standards and copyright protection (Alkhader et al., 2020). When considering the context of distributed networks, such as the ones comprising multiple AM services providers and original equipment manufacturers, there is a need to build trustful relationships among the different participants or to develop security approaches to establish a chain of trust among them (Kurpjuweit et al., 2019). Trust is also highlighted as one of the most prominent challenges within the literature around symbiosis networks (Madsen et al., 2015; Ponis, 2021). In the additive symbiotic network, similar challenges emerge: the need to trace AM resources used (including digital files, input materials, and AM technologies), the need to exchange sensitive information between symbiosis partners who do not have developed any relationship so far and thus, the need to develop trustworthy relationships. In this sense, there is a need to find tools that support not only the digital process chain (Kurpjuweit et al., 2019) associated with the networks but that also provide a trusted tracking solution (Alkhader et al., 2020), such as blockchain technology and hence, contributing to the development of the symbiotic exchanges, enhancing ISNs.

This study explores a new context for adopting blockchain technology: additive symbiotic networks. Overall, the study extends the existing literature regarding the synergies between AM, the adoption of blockchain technology and the ISN (Fig. 1). It intends to address the following research gaps:

- Ferreira et al. (2021) highlighted in their review that the development of industrial symbiosis strategies in AM research is still in its infancy and suggests as future research to map industrial symbiosis network initiatives that involve AM technologies and to study the feasible typologies of the networks comprising new business models and supported by new knowledge and innovative technologies.
- Industry 4.0 technologies may drive the implementation of a new generation of circular economy strategies, however, it is not clear what are the requirements to implement those technologies in a real case setting. For example, Patyal et al. (2022) theorize about the link between the adoption of Industry 4.0 technologies, such as blockchain and AM, and circular economy sustainable operations; however, those authors recognize the need to do substantial empirical work through a large-scale survey or a case study for validation of the proposed framework. Furthermore, Tseng et al. (2018) state there is a need to address how Industry 4.0 technological innovations can be used for data-driven analyses to generate liable information among industrial symbiosis partners and used to measure corporate culture and behaviour, including mutual trust to enhance industrial symbiosis processes.
- Xu & Viriyasitavat (2019) point out that adopting blockchain technology in a collaborative business process setting poses several interoperability challenges related to time, prejudice and trust in process execution and information. The application to real case scenarios, extending the existing studies related to financial trading to other domains of applications and describing factors that contribute to the creation of smart contracts requires future research.
- Ghimire et al. (2022) focus on focus on the synergies between AM and blockchain technologies. Those authors mention that despite the existing contributions in the literature for understanding how blockchain technology potentially affects supply chains those studies are not tailored to the AM context. Moreover, both technologies (AM and blockchain) have still not been used in a scalable manner, posing challenges for companies aiming to adopt them. There is no real-life

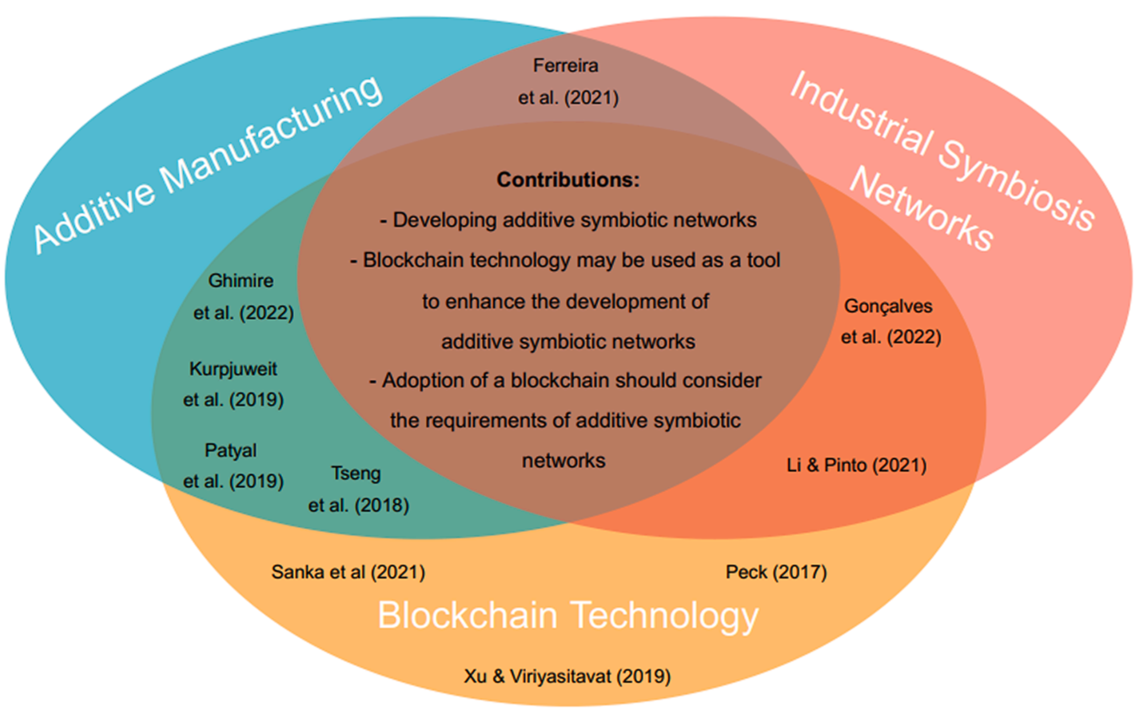

Fig. 1. Positioning of the study in the existing literature.

blueprint for developers or researchers to follow (Kurpjuweit et al., 2019).

- Peck (2017) and Sanka et al. (2021) refer that the adoption of blockchain technology should be carefully evaluated as it depends on the diversification of interests within the companies involved and the problem that the technology is trying to improve. So, there is still a need for more research in a real-case scenarios to find out how to frame the problem and identify requirements for the technology deployment.
- Gonçalves et al. (2022) and Li & Pinto (2021) show that for industrial symbiosis networks to succeed, companies should be trusted and trust each other; their relationships and transactions should be auditable and defined. However, they point out the need to develop more empirical studies on adopting a blockchain-based system to improve the industrial symbiosis process creation.

To contribute to the development of additive circular ecosystems, this study aimed to understand if blockchain technology may be an enabler of additive symbiotic networks. Three main research objectives are addressed: i) to characterize the flows exchanged between the stakeholders in an additive symbiotic network; ii) to identify the main activities performed by the stakeholders in an additive symbiotic network and iii) to identify the requirements to use the blockchain technology in an additive symbiotic network. A case study was developed about a symbiotic network in which AM technology is employed to valorize plastic waste. Polycarbonate (PC) sheets, a by-product, are used as input material for an AM process.

This paper is structured as follows: after this introductory section, containing the main research gaps and objectives of this study, Section 2 has the theoretical background, focusing on ISNs, the AM industry and the blockchain technology. Section 3 presents the main concepts around the development of additive symbiotic networks through adopting

Table 1
The industrial symbiosis creation framework.

Industrial symbiosis (IS) creation phases		Functional requirements	Target stakeholders	Tool requirements
Phase I - Preliminary assessment	- To understand sustainability and local conditions - Analysis of needs and requirements	Collecting intelligence to assess previous streams and regional attributes and to determine the sustainability and potential for creating IS	- Eco-industrial park/estate planners - IS facilitator	- Data from the process input and output - Geo-spatial related data - Statistical data sets - Historical cases of information capture and gathering
Phase II- Engage businesses	- To identify potential members and recruitment - To foster a cooperative culture - To create interest and awareness	- Create awareness and interest - Build trust - Build and grow networks of businesses	- Stated to be utilized via authoritative body or facilitation body - Individual businesses	No specific conditions. The preferred impact of these tools can be improved by relying on success cases that help to illustrate the benefits of IS
Phase III - Find synergy opportunities	- Share of Information and collection of data - To find synergy opportunities - Input/out and process analysis	To determine the potential synergetic relations between businesses	- Enterprises with interest in partaking in IS exchanges as utilizers of the platforms and IS administrators as hosts of platforms to match - Partaking organizations in self-driven IS as utilizers of non-platform-based stream matching methods - Network optimization and design: Planners of Eco-industrial estates/parks	- A matching mechanism based on Free market: details such as information on the partaking enterprise, location, textual definitions of waste at the buyer and supplier sides, requirements /availability regarding price, time and quantity. - A matching mechanism based on process input/output stream: company-detailed data regarding the flows of resources, the "wants" and "haves", and specific data - Design and Optimization of the Network: data needed for defining the physical system such as enthalpy, pressure, temperature, flow rate, chemical types of streams concentration
Phase IV- Business feasibility	- To analyze cost/benefits - Quality considerations - Regulatory and risk considerations	Offer decision support in selecting and planning for several IS-based options	Partaking organizations in IS exchanges or IS networks	Data needed by economic calculations and methods are freely accessible to be applied
Phase V- Implementing transactions	- Transaction creation - Environmental, societal and economic impact assessment - Reporting and monitoring	To manage the project, follow the evolution of the implementation of IS opportunities and assess the performance	IS orchestrators seeking macro-level information on ISN	- No particular necessities, except for entering data by IS practitioners - Input data necessities by every single performance assessment tool
Phase VI - Reinforcement and Document	- To capture success cases	Overall role of concrete IS cases dissemination of information	- IS orchestrators for indicating potential IS interchange - Organizations of self-driven IS by employing the current documentation for generating new IS ideas	Concrete information which describes the occurrence of IS cases and operating documentation by the tool upholder

Notes: IS – Industrial symbiosis; IS orchestrators - facilitators or eco-industrial estate/park planners.
Adapted from Yeo et al. (2019).

blockchain technology. It also presents the case study and explains the data collection process. The results and discussion are provided in section 4, and section 5 contains the study's conclusions.

2. Literature review

2.1. Industrial symbiosis networks

In a circular economy ecosystem, the ISN concept is related to the exchange of by-products and utility shares (including the reuse, recovery, recycling and commercialization of "waste" that can be used as secondary raw material). These exchanges of resources occur between companies and other entities in a local or regional industrial ecosystem system (Ferreira et al., 2019). This way, the circularity of materials and other resources is promoted in inter-organizational networks constituted by different stakeholders that continually exchange materials, by-products, and energy with minimum or zero waste produced. In short, we can theorize the industrial symbiosis development as translated into a network of different stakeholders interacting.

ISNs are defined by all the stakeholders who play an active role in it and act together with each other exchanging value (any beneficial action for the stakeholders engaged in a circular economy ecosystem), directly or indirectly (Ferreira et al., 2019). This value exchange is manifested through the sharing of resources or exchanges of information and knowledge. Mortensen & Kørnøv (2019) consider three different phases for the stakeholders' engagement in an ISN: i) awareness and interest in the industrial symbiosis; ii) reaching out for industrial symbiosis potentials, and iii) organization of new relations and rules' definition. In these three phases, having a platform for interactions between stakeholders provides space for trial and error and motivates a more experimental approach toward the emergence of ISN. Yeo et al. (2019) propose a six-phase framework for industrial symbiosis creation. The functional requirements, the stakeholders involved, and the tools used to operationalize each phase are summarised in Table 1.

The industrial symbiosis process brings benefits at various levels, namely, economic, environmental and social (Hein et al., 2017). However, there is not much debate in the literature regarding making industrial symbiosis effective within different contexts (e.g. Taddeo et al., (2017)). Madsen et al. (2015) stressed out that trust is an essential element in developing exchanges of resources between stakeholders. It is required to have trust not just in the facilitator entity (which can be the focal organization) but also in the other stakeholders since the facilitator needs to gather confidential or sensitive information to do the companies/stakeholders matching.

The implementation phase (phase V) makes the conversion of industrial symbiosis opportunities into a real circular ecosystem. After the opportunities become tangible, they are frequently coupled with efforts to monitor the impact of realizing those opportunities and continually improving them. Within this study, the researchers choose this phase, i.e., the implementation of transactions, as the object of study. The transactions may correspond to physical, monetary or informational and knowledge resources. Therefore, mapping the flows exchanged between stakeholders in an ISN is critical. Ferreira et al. (2019) gave valuable insight into doing this, showing how the methodology developed by Hein et al. (2017) could be used to map and analyze ISNs by assessing the power distribution among the symbiotic stakeholders.

2.2. Additive manufacturing as an enabler of circular economy strategies

AM is "*the process of joining materials to make objects from 3D models data, typically layer upon layer, as opposed to subtractive manufacturing and formative manufacturing technologies*" (ASTM, 2016). Adopting this industry 4.0 technology is considered a critical enabler of a circular economy and for achieving a set of sustainable development goals (Patyal et al., 2022). Also, it is essential to transiting to a circular economy ecosystem (Cruz Sanchez et al., 2020). It can influence the distribution of manufacturing and flows of goods and materials with many sustainable benefits (Despeisse et al., 2017) since it provides technological features to use a limited amount of materials and energy (not exceeding the quantity needed of materials to produce and create the product) (McDonald, 2016), as well as the fabrication of parts in small-batch sizes reducing the supply chain inventory levels (Yuan et al., 2022). More recently, several researchers have focused on how AM could help to overcome 2022′s most pressing supply chain challenges due to the aftermath of the COVID-19 pandemic (Arora et al., 2020; Scarpin et al., 2022) and due for to Russian-Ukraine 2022 War (Rae, 2022; Lim et al., 2022) such as port congestion, increasing freight prices, material scarcity, high inflation and challenging demand forecasting.

This type of manufacturing is critical to the realization of a circular economy, as it is decentralized and distributed; it eliminates wasteful steps of traditional manufacturing; it extends the range of products that can be manufactured; and it saves materials, time, and logistics. Hettiarachchi et al. (2022) assess how AM can enable a circular economy and how supply chain actors, key decisions, drivers, operational practices, and implementation strategies interact to operationalize AM in the circular economy context. In order to boost the circular economy, Kumar (2022) presents a thorough and up-to-date discussion on breakthroughs in AM, identifying new products and strategies for product development. While Gouveia et al. (2022) argue that to establish the role of AM in the future circular economy, there is increasing demand for data regarding its environmental and economic performance.

Several applications of AM technologies have recently been highlighted as having an important role in implementing circular economy strategies. Rosa et al. (2020) analyzed 30 studies regarding how AM can support the circular economy. Hettiarachchi et al. (2022) performed a systematic review comprising 51 journal articles to identify the conceptual elements of AM integration into the circular economy. An assessment and demonstration of a circular economy strategy for reducing CO_2 emissions through concrete recipe optimization is presented by Favier & Petit (2022). Sustainability and how AM impacts is examined from an environmental, economic, and social perspective by Arifin et al. (2022). Rodriguez Delgadillo et al. (2022) provide operational guidance to decision makers for improving AM processes in terms of quality and sustainability. Moreover, several studies claim that to achieve sustainable manufacturing, recycling and AM must be combined (Di & Yang, 2022; Stefaniak et al., 2022; Wu et al., 2022).

There are significant challenges and opportunities related to recycling and AM (Wu et al., 2022; Shanmugam et al., 2020). Studies like Haleem & Javaid (2019) and Rosa & Terzi (2021) highlighted that the AM contributes to a reduction in waste through recycling processes, thus promoting a reduction in the usage of raw materials. Plastic materials or polymers offer a variety of mechanical and chemical characteristics that can be used for a wide range of applications (Shanmugam et al., 2020; Mikula et al., 2021). Cruz Sanchez et al. (2020) argued that AM could be a tool for recycling plastic waste material and improving resource consumption efficiency. Currently, polymers play an essential role in the industry due to their specific properties such as high electrical/thermal insulation, possibility to operate in a wide range of temperatures, good mechanical properties (toughness, ductility, strength-to-weight ratio and stiffness) and corrosion and light-resistance (Vidakis et al., 2020). AM technologies can increase the potential to recover the value embedded in plastic waste.

According to Reich et al. (2019), upcycling plastic waste into filament for AM processes with an open-source waste plastic extruder is one way to overcome the barrier related to waste management and material and technological costs in the AM industry. Material extrusion 3D printers that allow printing directly from plastic pellets have been developed over the past few years (Alexandre et al., 2020). A series of devices that enable the material extrusion from plastic waste material is available in many variants. The filament extruder, for example, allows not only the production of granulated filament but also has a built-in grinder that supports the processing of any plastic (Mikula et al., 2021). Authors like Cruz Sanchez et al. (2015) have highlighted different development initiatives of open-sources small-scale plastic extruders that transform post-consumer waste into filament to feedstock 3D printers, namely: the RepRapable Recyclebot, the Lyman Filament Extruder, and the Filabot.

The extruder 3D printer can reduce the melt cycles in the fabrication of AM parts from recycled plastic materials and has proven to offer potential for distributed recycling with an improvement in the economic and environmental performance (Alexandre et al., 2020). Waste extruders are being used directly for shredding, preparing and processing waste filament for recycled use (Peeters et al., 2019). For example, the RepRapable Recyclebot is an open-source 3D printing waste extruder that can transform plastic into commercial quality 3D printing filament (Woern et al., 2018).

AM technologies' industrial applications promote circular production systems by employing recycled and reclaimed materials as inputs for some AM processes (Despeisse et al., 2017). For example, unused powder from the metal AM can be locally filtered and directly reused (Vayre et al., 2012). The percentage of unused powder is highly dependent on the powder selection and the target application; nevertheless, Vayre et al. (2012) refer that up to 95 % of the unused metallic powder can be reused. Despite all these advancements, there is still a minor amount of research relating AM with ISNs development (Ferreira et al., 2021).

2.3. The blockchain technology

Blockchain gained international momentum when it first enabled mistrusting parties to perform transactions without requiring a centralized trusted third party (Nakamoto, 2008). Blockchains also referred to as distributed ledgers, can be used to support more than just monetary transactions. The introduction of smart contracts that, when executed, change the state of all nodes that are part of the blockchain enables distributed applications (Xu and Viriyasitavat, 2019).

Blockchain technology gives access to information that allows stakeholders to validate and exchange information about demand, specifications, supply, and prices (Chidepatil et al., 2020). Ponis (2021) highlighted that the potential of blockchain technology to support environmental sustainability was related to the capability to provide a verifiable record of who and what is exchanged and, consequently, what every actor has at a given time. This technology can serve as a distributed platform for trading recycled and reclaimed materials allowing profit improvements, assisting companies in connecting to other stakeholders, and stimulating the exchange of wastes between them without any intermediaries (Kouhizadeh et al., 2019). Besides tracking materials, blockchain technology may be valuable in terms of exchange, facilitating the operationalization of potential regulatory entities or even external audits. Smart contracts can be set up where returns can be financed and completed via electronic means (Xu and Viriyasitavat, 2019).

A blockchain's information is very difficult to extinguish or corrupt since blockchains are replicated across a peer-to-peer network (Peck, 2017). There can be two types of blockchains (Wüst & Gervais, 2018):

- permissionless - any node can take part of the network that supports the blockchain, leaving whenever it decides to and can read or write data to the blockchain, only being regulated by a consensus algorithm. They have low throughput and high latency but support many writer/reader nodes.
- permissioned – the node capabilities differ among themselves, some being allowed to read and write data to the blockchain, while others are only allowed to read data. They have a high throughput with lower latency and support many reader nodes but only support a small number of writer nodes.

At first sight, blockchain can potentially be used in a large spectrum of situations (Atzori, 2017). However, Peck (2017) stresses the need to justify the use of blockchain and choose the adequate type of blockchain considering the needs of a company or service (Fig. 2.).

Despite several attempts made by scholars and industrial sectors to apply blockchain technology for business process improvement, adopting this new and disruptive technology is still in an earlier stage (Xu & Viriyasitavat, 2019).

3. Methods

3.1. Developing additive symbiotic networks with the adoption of the blockchain technology

The organization of manufacturing activities is changing with the emergence of new advanced manufacturing technologies. Within the AM industry, there is potential to rethink how raw materials are processed to minimize the resources used as input for an AM process, promoting the direct use of by-products, such as waste, as material input for production (Despeisse & Ford, 2015), contributing to the development of strategies as the industrial symbiosis. Ferreira et al. (2021) highlighted some aspects related to the alignment between the AM and the development of circular ecosystems, namely:

- Material savings - because it uses the exact amount of material necessary to manufacture the product and sometimes tooling is not even required, AM reduces the need for raw materials and waste generation.
- Flexible manufacturing strategies - AM strategies may contribute to the reduction of logistics activities and transportation needs.
- Design-based economy - AM allows parts to be manufactured using 3D files directly, with no requirements for manufacturing expertise, reducing the barriers related to the knowledge of the product and the manufacturing processes.

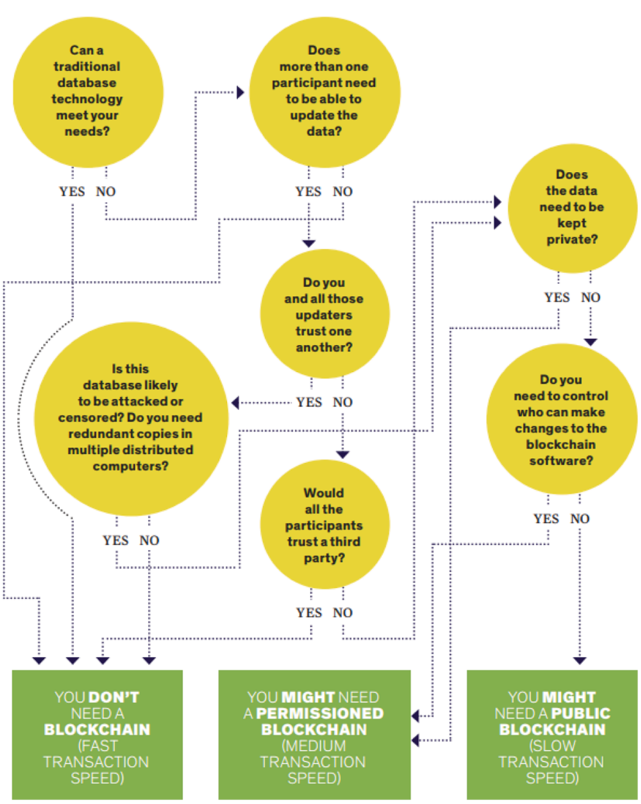

Fig. 2. Can blockchain technology solve a company's or service's problem? Retrieved from Peck (2017).

- Maintenance interventions and hard repair save space and storage needs for spare parts since AM can produce them when necessary.

Thus, as the literature suggests, the AM industry promotes the implementation of circular ecosystems, creating opportunities to develop ISNs within this context (the so-called additive symbiotic networks). According to Hein et al. (2017), an ISN's economic and social exchanges are characterized by value flows between stakeholders, creating a value network. A value network arises from the exchange of resources within an ISN comprising the strategic and operational interdependencies among the different stakeholders (Ferreira et al., 2019). The inter-relationship between the various stakeholders is an opportunity but also includes challenges related to the transaction costs, the power distribution among stakeholders, the need for intermediaries in the system, and interdependences to capture, create, and deliver value (Kanda et al., 2021).

Yeo et al. (2019) emphasized that few information and communication technology tools are available to support the industrial symbiosis process implementation phase. They describe the *Core Resource for Industrial Symbiosis Practitioners* as a platform to support the industrial symbiosis progress tracking and project management. Furthermore, other tools could be applied, for instance, performance measurement tools that generate metrics to assess the performance of industrial symbiosis exchange. However, such approaches are usually easily applied to either single organizations or single supply chain systems, and even though the principles can be applied to different organizations in cross-industry networks (as the ISNs), those efforts are often impeded due to confidentially issues, data gaps, and discrepancies (Tseng et al., 2018). Therefore, there is a need to find tools that contribute to developing such symbiotic exchanges between different industries, enhancing the development of ISNs.

The blockchain technology can be a tool to deal not only with the challenge related to trust (Ponis, 2021) among the different stakeholders but also to provide the necessary technical support for the ISN implementation phase. It can securely store information such as the stakeholders' data, the process characterization, the energy consumption, and the trace products and materials (Kouhizadeh et al., 2020; Wang et al., 2021) (Godina, Bruel, Neves, & Matias, 2022). Smart contracts can assure that waste across the value chain is minimized, for example, by including supplier performance criteria for waste reduction metrics and by identifying where and how the wastes can be used to minimize their environmental impact within that supply chain (Kouhizadeh & Sarkis, 2018). Moreover, in their study, Gonçalves et al. (2022) highlighted that industrial symbiosis networks could benefit from adopting blockchain technology and related concepts to capture and share information regarding the number, quality and value of waste exchanges.

Adopting blockchain technology from a technological standpoint has been addressed several times (e.g. Ganeriwalla et al., 2018; Koens & Poll, 2018; Peck, 2017; Wüst & Gervais, 2018). Despite the already existing body of knowledge, blockchain technology is still in its early developments when applied in ISNs settings, with multiple entities and companies exchanging resources (Gonçalves et al., 2022). Few works have been developed relating blockchain technology with the AM industry (which also reveals the potential to create additive circular ecosystems) (Kurpjuweit et al., 2019). Recent works have only focused on copyright and intellectual property protection or as an anti-counterfeiting mechanism (Holland et al., 2017; Kennedy et al., 2017; Kurpjuweit et al., 2019; Mandolla et al., 2019).

This study focuses on the development of additive symbiotic networks to understand if blockchain technology may be used in this setting as a tool to support the networks' implementation phase. It intends to characterize an additive symbiotic network (namely, its main flows and stakeholders) and to find out the requirements for using blockchain technology in that symbiotic network.

3.2. The case study method

The case study method was chosen to carry out this study. The case study is considered a research method that focuses on comprehending the dynamics within single settings, representing a detailed empirical description of a specific phenomenon in which various sources of evidence are used (Eisenhardt, 1989; Yin, 1994). According to Voss et al. (2002), the case study method can lend itself to early exploratory investigations where the phenomenon is not entirely understood and some variables are still unknown. Case studies could have explanatory, descriptive, or exploratory purposes (Yin 2003). Since this study is exploratory in its nature, the case study was considered the most suitable method. In this study, the researchers adopted a positivistic approach to the case study method where reality is seen as external to the observers, following Yin's (2009) research design logic. Fig. 3 represents the different steps from the design logic and how they were considered in this study for conducting the case study.

Chertow (2000) stressed three types of actions that could occur in an industrial symbiosis relationship: sharing common services' needs, sharing infrastructures and by-products exchanging market. This study focuses on this last action: the by-products exchanging market - where one or more industries or sectors can use other production wastes as materials inputs for their processes (Ferreira et al., 2019). Considering the focus of this exploratory work, one single case study was selected due to its representativeness of the phenomenon under investigation: the usage of AM technologies for waste valorization within an ISN currently in an implementation phase.

Regarding the data collection, different data sources are used to collect data for conducting the case study, allowing the triangulation and improving the construct validity of the study (Piekkari et al., 2009). The data collection process is described in detail in sub-section 3.3.

Following Yin's (1994) suggestions, four measures were taken to guarantee the quality and the feasibility of the case study, namely:

- Validity of constructs: utilization of different sources of evidence – secondary and primary data was collected from distinct sources. The experts involved developed, discussed, and validated a report with the data analysis.
- Internal validity: main conclusions and findings were presented to the experts involved in the research. The high degree of internal validity assures the theoretical generalizability.
- External validity: the case study's main objective was not to generalize the results. The unit of analysis was clearly defined, and the case study scope was given to support the results to comparable cases.
- Reliability: the protocol of the case study was created by employing a model from the existing literature. Specifically, this research applies the methodology from Ferreira et al. (2019) to develop and evaluate the ISN.

3.3. The "from Trash to treasure" case study

An exploratory case study related to an additive symbiotic network was carried out. The AM technology in this case study is supplied by a company located in Texas, USA, that sells 3D printing equipment and services using plastic waste streams as a by-product. Re:3D names the company under study. This company is pioneering innovations with the aim to reduce the cost and social barriers to 3D printing while enabling circular economies and changing traditional supply chains. With customers spread in more than 50 countries worldwide, re:3D's main product is Gigabot, the world's largest industrial fused filament fabrication 3D printer. Recently, re:3D modified this printer to enable 3D printing from pellets and reclaimed plastic waste, allowing sustainable, affordable, and locally-driven manufacturing. The company introduced the AM technology in 2013 and currently has two types of 3D printing equipment: i) Gigabot X (GBX) pellet printers; Gigabot 3 + filament

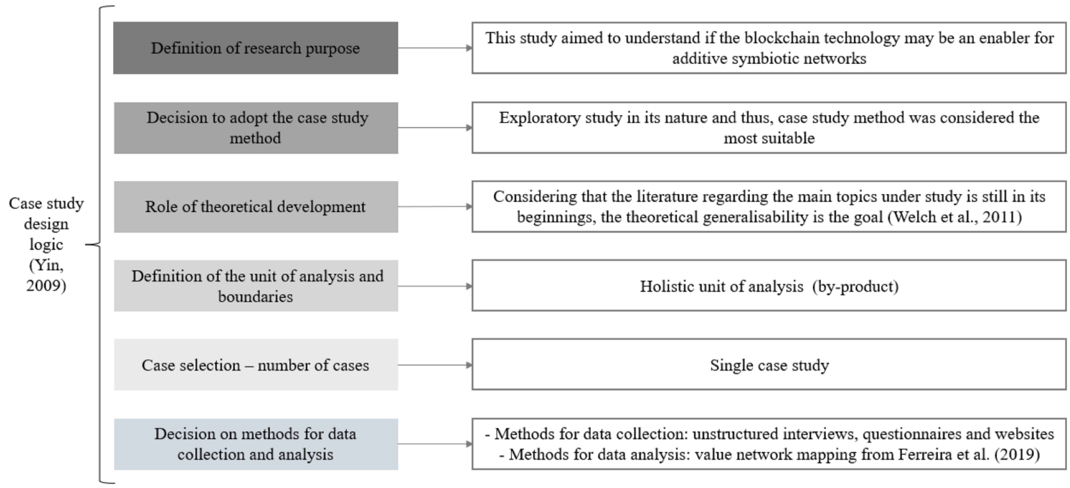

Fig. 3. Case study design logic followed in this study.

printers. re:3D uses both fused granular fabrication and fused filament fabrication technologies. The company has its own fabrication facility located in Austin, Texas, and beyond producing 3D printers, it also offers 3D printing contract services, design, consulting, and education.

Printing with a bigger nozzle whereas utilizing pellets or flake is 5 to 10 times more economical when compared to the traditional filament. The GBX's larger nozzle can decrease printing time up to 17 times compared to fused filament fabrication printers. The GBX can print with 1/8″ plastic granules melting below 270 °C, and in this way, decreasing the dependence on printing using filament at the same time as supporting plastic granule mixing. A depiction of GBX with some of its features is presented in Fig. 4.

The researchers focused on one specific project in which the company took part – the "From Trash to Treasure" project that made it possible to print goods directly from plastic waste. This project is an example of an ISN where different stakeholders exchange value between them. It was considered a single unit of analysis for this case study, corresponding to the by-product PC sheets.

The case study comprises four stakeholders (Table 2.): i) re:3D – a start-up that produces and sells 3D printing services and technologies to valorize waste; ii) HID Global - a manufacturing company that produces ID cards (where the by-product is generated); iii) Austin Resource Recovery - the organization that promoted an event which allowed for the different stakeholders to meet and iv) Austin Habitat Humanity ReStore - the store where goods printed from the by-product were displayed. These entities were selected for this work due to their potential to create and develop an additive symbiotic network.

Every year, the Austin Resource Recovery department hosts an event called the Austin [Re]Verse Pitch for companies within the Austin community that are creating waste that could be used in other areas of business or sectors (austintexas.gov, 2020). Among the companies that participated in this event in 2019, HID Global, a security and identity company, has pitched about PC sheets. This by-product results from producing identification cards in the company's factory and is made in significant amounts, approximately around 410 kg per week (HID Global, 2021b). During the competition, re:3D was able to pitch the "Design: by re:3D" for a line of furniture – The Austin Habitat for Humanity ReStore, where home goods and art pieces were intended to be printed on GBX directly from the HID's PC sheets.

Small vases were included among the products produced by re:3D

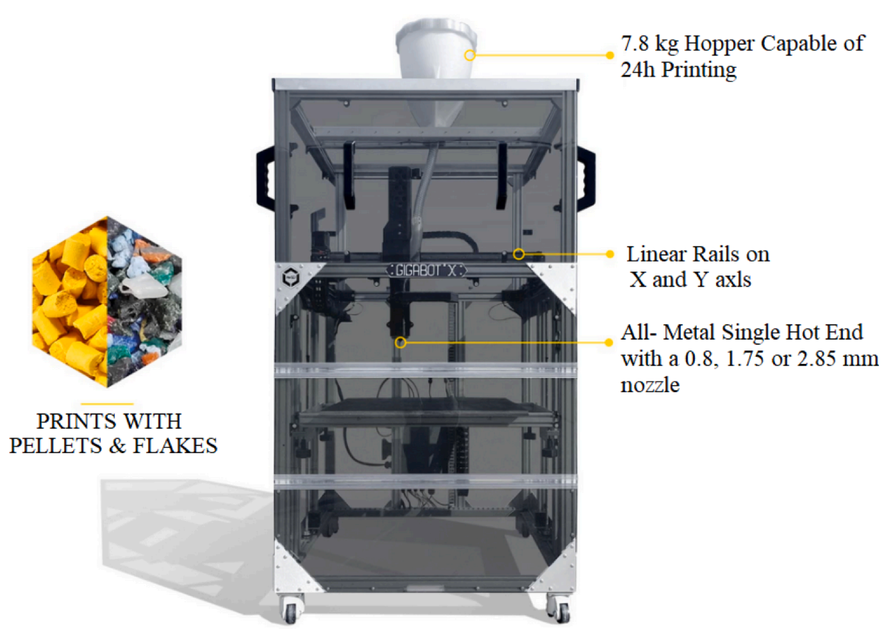

Fig. 4. Gigabot X (GBX) printer. Retrieved from (re:3D Inc, 2020a).

Table 2
Stakeholder description.

Stakeholders	Description	Activity
re:3D	Start-up that produces and sells 3D printing services and technologies	3D printing services, technologies, and printers
HID Global	Manufacturing company that produced ID cards	Company whose main product line is secure identity products. The production of such products generates PC wastes that can be used as by-products (around 410 kgs of clean PC waste per week)
Austin Resource Recovery	Austin city's waste management utility	Promoted an event called "Austin [Re]Verse Pitch Competition"
Austin Habitat for Humanity ReStore	Non-profit home improvement stores and donation centres	Store that displayed the first pieces of furniture printed from plastic waste

from the PC sheets. The maximum speed of extrusion rate for the GBX printer is 0.8 kg/hour. Considering that the weight of a small vase is 0.8 kg, it will take 1 h for the printer to print one unit of product. Re:3D determined that 95 % of the PC sheets that go into the granulator are printed. However, the extra 5 % is lost in processing. Again, if a small vase is 0.8 kg, there is needed for 0.8 kg of PC sheets per vase.

As Fig. 5. shows, it all started in 2018 when re:3D had the opportunity to fund the creation of the GBX 3D printer. In 2019 the pitch made by re:3D was the winner of the Austin [Re]Verse Pitch Competition, and in 2020, almost a year later, the first pieces of furniture printed from PC sheets were displayed. This research was developed in the year 2020, and, at that time, this project was under a trial phase, meaning that the first pieces of furniture created by re:3D were being featured to assess possible interest.

As previously highlighted (Table 1), the industrial symbiosis creation process comprises six main phases that are aligned with the case study under analysis:

- "Phase I - Preliminary assessment", "Phase II- Engage businesses", and "Phase III - Find synergy opportunities" are related to the [Re] Verse Pitch competition phase of the project, where the network of contacts is established, and the first interactions between stakeholders occur.
- "Phase IV- Business feasibility" is linked to the last stage of the [Re] Verse Pitch Competition phase and before displaying the first pieces of furniture.
- "Phase V - Implementing transactions" translates the project's current state at the time of this study– the phase of implementing transactions of resources among the symbiotic stakeholders.

3.4. Data collection

Secondary and primary data were collected using distinct methods and sources. Regarding the primary data (Table 3), the research team conducted unstructured interviews with the experts representing the stakeholders involved in the network. The experts' profile is also available in Table 3. It is critical to highlight that the Austin Resource Recovery stakeholder is represented in this study by the Austin Young Chamber, a Chamber of Commerce, as one of the entities involved in the Austin [Re]Verse Pitch Competition organization. Moreover, the Austin Habitat Humanity ReStore is represented by the company re:3D.

Considering the network of the case under study, four questionnaires (A, B, C and D available in Appendix 1 – Supplementary files) were devised to capture the stakeholders' different perspectives. The main aim was to map the stakeholders and resources in the network and identify and quantify the value flows exchanges between them. In the first stage, questionnaire A was developed for re:3D to identify and map the main stakeholders and wastes exchanged, allowing a characterization of the overall network. In a second stage, to identify and quantify the value flows and transactions, customized questionnaires (B, C and D) were sent to each stakeholder (re:3D, HID Global and Austin Young Chamber, respectively).

Secondary data was collected from the companies' reports on the project "*From Trash to Treasure*" (specifically, an executive summary of the event Austin [Re]Verse Pitch (re:3D Inc, 2019)), along with relevant data from the companies and organizations websites. This data set was used to support the design of the network's first draft and the identification of primary stakeholders.

3.5. Value network mapping

A three-step model for mapping ISNs proposed by Ferreira et al. (2019) was followed, considering the criteria developed by Hein et al. (2017) for quantifying the value flows and the methodology and scores developed by Feng (2013), to create a value flow matrix to assess the power distribution of the network's stakeholders. This value flow matrix is the ultimate result of the value network mapping, which addresses this study's first research objective, characterizing the flows exchanged between the stakeholders in an additive symbiotic network. The following sub-sections describe the different steps of the model to create a value flow matrix characterizing the network under study.

3.5.1. Identification of the network's stakeholders

The first step is to determine the focal organization and the stakeholders involved in the network through the primary data collected from the unstructured interview and questionnaire A and through secondary data. The focal organization is responsible for conducting negotiations and investigations and regulating the symbiosis's implementation and operationalization. In the case under analysis, the re:3D was the company that had a 3D printer able to print directly from plastic waste - the GBX printer. The company developed a whole system that allowed to grind, dry and feed the plastic waste into the printer (re:3D Inc, 2020b).

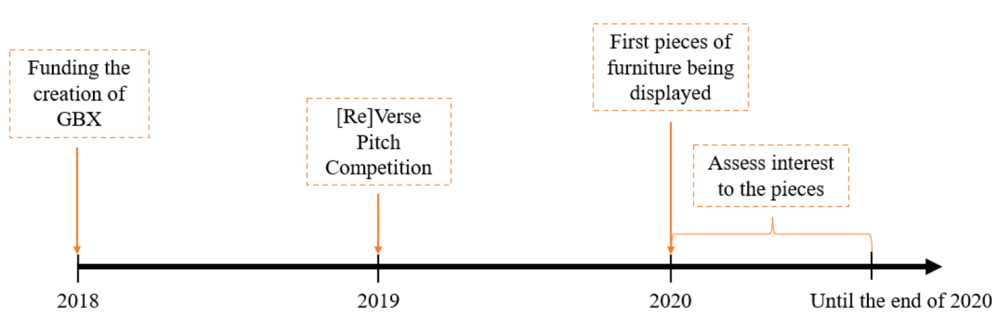

Fig. 5. Timeline of the project "From Trash to Treasure".

Table 3
Primary data collection.

Research phase	Objective	Data collection	Stakeholder	Expert's profile Function	Professional experience (years)
1st phase	• Case study description • Identification of wastes and stakeholders • Identification of the focal organization	Unstructured interviewQuestionnaire A	re:3D	Co-founder & catalyst	20
2nd phase	• Value flow identification and quantification • Identification of transactions	Questionnaire B	re:3D	Co-founder & catalyst	20
		Questionnaire C	HID Global	Environmental, Health and Safety Leader	5
		Questionnaire D	Austin Young Chamber	Circular Economy Program Manager	9

It is the entity responsible for all necessary treatment before incorporating the waste and transforming it into new products. Also, it is responsible for finding partners that could provide them with plastic wastes as secondary raw materials and others that would be able to sell their final products. Therefore, in this study, the re:3D was considered the focal organization.

Different entities interacting with each other constitute the ISN. These entities are the so-called stakeholders. There are different types of stakeholders: i) direct partners - the ones directly involved or plan to be involved in the exchange of resources; ii) indirect partners - the ones that can develop an indirect type of collaboration however necessary to support the exchange of resources within the network (Ferreira et al., 2019). In the case study, the direct partners are:

- **HID Global:** Headquartered in Austin, Texas, HID Global has over 3 000 employees worldwide and operates international offices that support more than 100 countries (HID Global, 2021a). HID powers the trusted identities of the world's things, people, and places. Every day, millions of people use HID products and services to securely access physical and digital places. HID products are used to verify transactions, open doors, track assets, find information, digital access networks, and connect with others.

As a material supplier, HID Global participated in the fourth [Re] Verse Pitch Competition in 2019. At that time, the company produced around 1640 kgs per month of PC skeletons from dye-cut ID cards (Reverse Pitch Competition, 2019). All the material was being sent to a landfill, and HID Global was looking for a more sustainable solution. This type of waste stream was possible to print with because PC is a very common 3D printing material, and the company's filament printing on GBX prints with PC regularly. Also, all the production process of the identification cards is done in a "clean" environment, which means that the waste is extremely clean (one of the advantages of using it because dirt can cause clogs and other issues in the printing process).

Before using the PC sheets in a 3D printer, there is a need for waste treatment: collection, stacking, grinding, drying, sifting, and printing. The company re:3D is responsible for all these processes associated with waste recycling. Within the symbiotic network, the company HID Global can be seen as responsible for producing the by-product used to make furniture. HID Global provided to re:3D, within the *From Trash to Treasure* case study, approximately 907 kgs of PC sheets resulted from creating ID cards.

- **Austin Habitat for Humanity ReStore:** with the location in Austin and San Marcos, the Austin Habitat for Humanity ReStore is a non-profit organization with a donation centre and a discount home improvement store. The company is committed to increasing access to low-cost building materials for the community and home improvement supplies and redirecting valuable and reusable items from landfills (ReStore, 2021).

At the Austin location, 4 miles away from the re:3D's location, the company positively impacts their community by reusing, reselling, and recycling materials. The company can recycle different materials from various metals, wood, paper, cement, ceramic, glass, plastic, and many others.

Within the "*From Trash to Treasure*" project, the ReStore teamed up with re:3D to sell pieces of furniture, décor and other household items from plastic waste and reclaimed materials – namely, the small vases. The ReStore also allowed re:3D to install a small industrial grinder in one of their installations for grinding the PC sheets into PC flakes. After it, the transportation of the PC flakes and their use in the 3D printer is re:3D's responsibility.

The pieces of furniture, including the small vases, started to be displayed in 2020. However, since it was a trial period, the sale would likely be negative at the moment, but with time, there is expected to be positive revenue.

As indirect partners, it was considered:

- **Austin Resource Recovery -** The Austin Resource Recovery, which within this case study represents the Austin [Re]Verse Pitch, is the only indirect stakeholder and is a non-profit subsidiary of the City of Austin. The Austin Resource Recovery department of the City of Austin offers a broad range of services designed to transform waste into resources while keeping the community clean (austintexas.gov, 2021). These services include residential curbside collection of trash, recycling, composting, and yard trimmings. Two departments of the City of Austin, namely the Austin Resource Recovery Department and the Economic Development Department, have joined efforts to launch the Circular Economy Program, which mission is to attract, grow and retain businesses, entrepreneurs, and non-profits, to attract investment, and to support the necessary infrastructure for resilient circular economy in Central Texas (austintexas.gov, 2019). The City of Austin Circular Economic Program and some community partners launched the [Re]Verse Pitch Competition. The competition is designed to inspire profitable new ventures while keeping materials out of landfills. The project "From Trash to Treasure" was the winning of the fourth annual [Re]Verse Pitch Competition. The Austin Resource Department is represented in this study by an expert belonging to the Austin Young Chamber.

3.5.2. Identification of value flows

The second step of the model is related to identifying value flows. According to Ferreira et al. (2019), a value flow exists when a stakeholder controls a relevant resource to another stakeholder. The flows exchanged between indirect and direct stakeholders are represented in Fig. 6, with dashed arrows and filled arrows, respectively. To identify

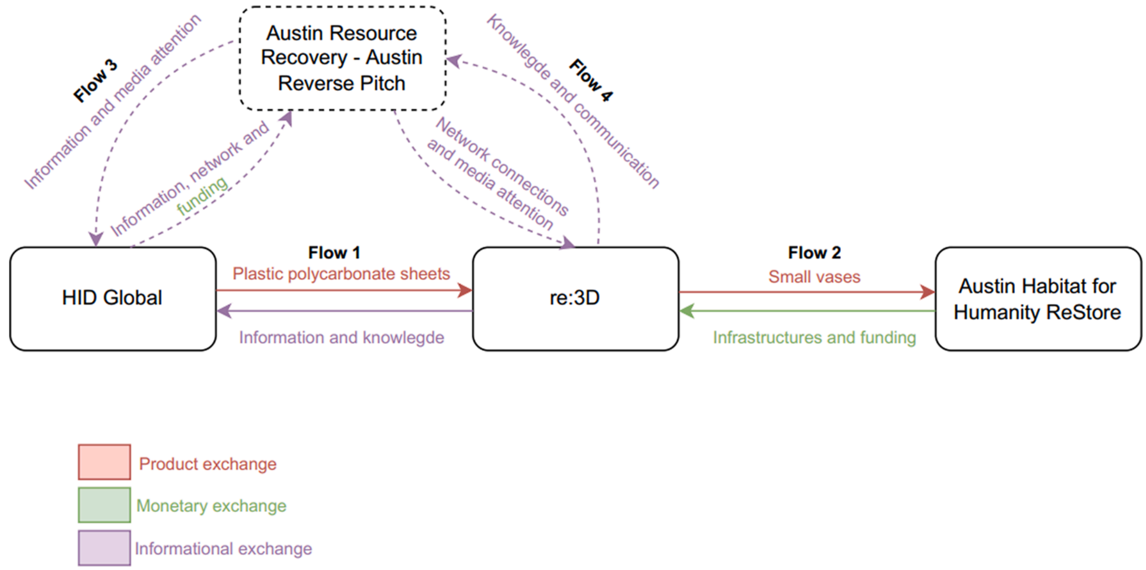

Fig. 6. Value flows exchanged among the stakeholders in the From Trash to Treasure case study.

the flows, primary data was used, namely data from part I of questionnaires B, C and D.

Each flow is constituted by a two-way relation: the direct flow and the reciprocal flow representing the inverse relationship. The "*From Trash to Treasure*" value chain can be modelled through a network with different resources exchanged in the direct flows: PC sheets, small vases, knowledge and communication and information and media attention (Fig. 5.). Only the direct flows, as well as the respective resources exchanged, are characterized in Fig. 4, and they can be described as follows:

- **Direct flow 1** – PC sheets are a by-product from HID Global, resulting from producing ID cards. This waste was meant to be sent to a landfill. However, it was noticed that this network's focal organization could be used as a material input to produce furniture pieces, for example, small vases, after receiving the necessary treatment.
- **Direct flow 2** – After receiving the by-product, the focal organization is responsible for using it as a material input in an AM process to produce the new pieces of small vases. These pieces are then sold in a store called Austin Habitat for Humanity ReStore.
- **Direct flow 3** – The Austin Resource Recovery does not have any monetary revenue; however, it helps them host events like the Austin [Re]Verse Pitch Competition because of their networking and relationships with material suppliers and innovators alike. Within the *From Trash to Treasure* case study, HID Global communicates the amount and characteristics of the wastes produced, reviews the business plans of each innovator, and selects which initiative they would likely be more receptive to.
- **Direct flow 4** – the focal organization is responsible for providing Austin Resource Recovery with information about the utility and possible uses of the wastes. Also, the focal organization helps Austin Resource Recovery get media attention and exposure by participating in and winning the competition.

Intrinsic to all the direct flows above-mentioned, there are reciprocal flows, specifically:

- **Reciprocal flow 1**: information and knowledge (given by the focal organization to HID Global on how to use the PC sheets wastes as a secondary raw material in 3D printers to produce new products).
- **Reciprocal flow 2**: infrastructures and funding (the ReStore allowed the focal organization to install a grinder in their installations for grinding the PC sheets before incorporating them in the 3D printer, and also, a percentage of the sales accomplished by the ReStore is given to the re:3D company).
- **Reciprocal flow 3**: network connections, media attention and exposure (the Austin Resource Recovery allows for interactions between companies that produce wastes and companies that can use those wastes as materials inputs for their processes, instead of deposing the wastes in the landfill).
- **Reciprocal flow 4**: Information, network and funding (the Austin Resource Recovery provides to the focal organization information about potential material suppliers and end-users costumers, enabling networking between the different stakeholders of the chain and funding the winner project of the [Re]Verse Pitch competition).

3.5.3. Value flow matrix to characterize the value flows exchanged between stakeholders

To quantify each of the value flows, the "urgency" and "dependence" criteria defined by Ferreira et al. (2019) were used. Through the use of questionnaires B, C and D (namely the primary data from part II), the experts representing the stakeholders involved were asked to quantify the scores for each criterion. The scores attributed to each value flow (direct and reciprocal) are available in Appendix 2. The value flow scoring is a subjective judgment; therefore, the aim was to determine if each stakeholder's preference was truly captured.

Combining these two criteria generates an aggregated score that explores the power distribution among symbiotic stakeholders, i.e., the stakeholder's desire to be involved in the value exchanges. The aggregated value scores developed by Feng (2013) for the "urgency" and "dependence" criteria are used in this study. An explanation of how to assign the correct aggregated value for each value flow within the network is given, and it is available in Appendix 2.

The value flow matrix is presented in Table 4. It allows characterizing the flows exchanged between the stakeholders in this additive symbiotic network, addressing the first research objective of this study. Each cell contains the designation of the value flow from the stakeholder in the row to the stakeholder in the column, as well as the respective resources exchanged and the aggregated score.

4. Results and discussion

Through the value network mapping of an additive symbiotic network, this case study demonstrates the AM industry's potential for

Table 4
Value flow matrix for the project From Trash to Treasure.

From:	To: re:3D	HID Global	ReStore	Austin Resource Recovery
re:3D		**Flow 1 - reciprocal**Information and Knowledge (0.54)	**Flow 2 - direct**Small vases (0.51)	**Flow 4 - direct**Information and Media attention (0.54)
HID Global	**Flow 1 - direct**PC sheets (0.76)			**Flow 3 - direct**Knowledge and Communication (0.76)
ReStore	**Flow 2 – reciprocal**Infrastructures and Funding (0.76)			
Austin Resource Recovery	**Flow 4 - reciprocal** Information, Network connections and funding (0.96)	**Flow 3 - reciprocal** Network connections and Media attention (0.76)		

developing ISNs, as already highlighted in studies such as Ferreira et al. (2021) and Sauerwein & Doubrovski (2018). From the value flow matrix presented in Table 4 in the sub-section 3.5.3, it is possible to characterize the main flows exchanged in an additive symbiotic network and conclude about the stakeholders' power in that network. The aggregated score used to quantify the flows allows for the conclusion that there are stakeholders with different levels of power. More specifically, in the case of this symbiotic network, the stakeholders re:3D and Austin Resource Recovery are considered to hold the most power since they exchange the flow with the highest aggregated score.

Moreover, since the additive symbiotic network under study is in the implementation phase of the industrial symbiosis creation process, the value flow matrix presented in Table 4 also allows linking the value flow exchange to the two main activities involved in the implementation phase of the industrial symbiosis creation process. It should be noted that the environmental, social, and economic impact assessment within this case study scope was excluded. The main activities included in an additive symbiotic network are:

- **Establish transactions** – Two types of transactions occur in this network:
- Physical transactions of two resources: waste material PC sheets (concerns with the quantity and quality of the PC sheets used in direct flow 1) and small vases (quantity exchanged in direct flow 2).
- Financial transactions that will correspond to the monetary value generated by selling the resource small vases (direct flow 2). Since the project is under trialling by the end of this research, this financial flow was not included in the study.
- **Monitoring and reporting**: which correspond to information about the quantity of plastic waste used in the AM process, as well as to the knowledge about the use of AM technology (exchanged in reciprocal flow 1) combined with the information about the number of small vases produced, sold and respective price of sale (exchanged in direct flow 4).

Considering an additive symbiotic network that is under the implementation phase, the main activities performed in the network, and additionally considering the existing tools for supporting this implementation phase, as emphasized by Tseng et al.(2018), there is space to explore the adoption of the blockchain technology within such networks. Moreover, exploring the blockchain technology in this setting may potentially contribute to the small quantity of research that relates the synergies between the AM and Industry 4.0 technologies, corroborating studies by Haleem & Javaid (2019), Kurpjuweit et al. (2019) and (Li et al., 2021).

The blockchain technology provides many advantages that may promote an efficient implementation of the network that goes beyond its purpose of financial transactions (Gorkhali et al., 2020), such as distributed cloud storage, supply chain management, smart property, ownership, Internet of Things (Xu & Viriyasitavat, 2019) and royal distribution (Wüst & Gervais, 2018). However, even though there is an excellent opportunity to use the blockchain technology within the scope of additive symbiotic networks, there is a need to understand if the blockchain technology may be adopted in such settings (Gatteschi et al., 2018). More specifically, it is necessary to identify the requirements for using blockchain technology within an additive symbiotic network. Consequently, in this study, we applied the decision chart developed by Peck (2017), previously presented in Fig. 1, to determine if and how the blockchain technology could be applied to the additive symbiotic network under study. In the following bullet points, using the set of evidence collected in the case study, we provide an answer to the set of questions composing the decision chart:

i) *Can a traditional database technology meet your needs*? The answer is no. The conventional core logic databases from each stakeholder involved in the symbiotic network would need to have a specific function for the exchange process, and all the databases should be connected. Also, within this case study, data about what a company typically considers a "waste" (PC sheets quantity and quality) and data about the final product (small vases) need to be shared among stakeholders (flows 1 and 2). Additionally, when considering the AM industry, there may be a need to track the quality of the inputs of the additive material during the exchanges, which is impossible to achieve using just a traditional database.

ii) *Does more than one participant need to be able to update the data?* The answer is yes. At least two of the stakeholders involved in the network need to change and update the status of the transactions - the network founder and maintainer (which within this case study would correspond to Austin Resource Recovery), the moderator of the network (which would correspond to the focal organization – re:3D) and/or another one who audits all transactions and relations in the network.

iii) *Do you and all those updaters trust one another*? The answer is no. Since new relationships are being created and developed in ISNs, and most stakeholders belong to different sectors or industries, no trust relationships exist between them. In the case of the AM industry and since AM is still emerging in the context of circular ecosystems, no mechanisms of trust or cooperation have been established yet with other industries. Additionally, within this case study, this additive symbiotic network is an emerging network that arises from a competition where the different stakeholders did not have any relationship between them so far and consequently did not know each other and did not have trust mechanisms developed.

iv) *Would all the participants trust a third party*? The answer is no. The stakeholders would need to trust again in an entity outside of their sector with no previous relationship.

v) *Does the data need to be kept in private*? The answer is no. The data does not need to be private, so the stakeholders involved in the exchanges can monitor each transaction's status. More specifically, within this case study and when considering AM technologies and products, there is a need to keep available information regarding the main processes and technologies used to transform the recycled materials into value-added products and information regarding the percentage of waste material used (reciprocal flow 1) should be accessible. Additionally, information such as quantity produced and sold regarding the final products (reciprocal flow 2) should also be available to all the stakeholders involved in the transactions.

vi) *Do you need to control who can make changes to the blockchain software*? The answer is yes. For example, reciprocal flow 4 has the highest value of the aggregated score. Consequently, it can be concluded that Austin Resource Recovery and the re:3D are the stakeholders with the highest power in this network. On the other hand, the direct flow 2 has the smaller aggregated score; thus, the ReStore stakeholder can be considered one of the stakeholders with low power within this network. These differences in values regarding the power of the stakeholders can contribute to trust imbalances between them. Thus, there is a need to have a unique entity responsible for creating and maintaining the network that would correspond to the focal organization (namely, re:3D).

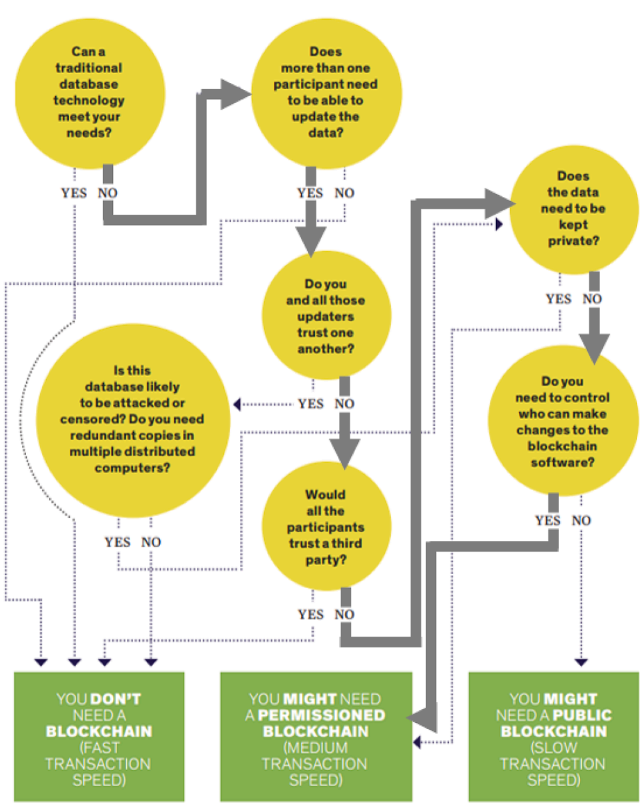

Fig. 7. Can blockchain technology help to implement an additive symbiotic network? The decision path (i.e. arrows in grey) for the case study.
Adapted from Peck (2017).

Fig. 7 complies the decision path for the case under study, and it is suggested to use a permissioned blockchain. Considering this decision path, it is possible to conclude that the requirements to use the blockchain technology in additive symbiotic networks are: i) the database should allow all the stakeholders to connect and support the main activities involved in an additive symbiotic network in the implementation phase of the industrial symbiosis creation process; ii) at least two of the stakeholders in the network need to update the data in the database; iii) no corporation or trust mechanisms exist between the stakeholders; iv) the stakeholders do not trust in a third party, v) data does not need to be kept in private and vi) there is need to have an entity responsible for making changes in the database.

The case study demonstrates the use of a permissioned blockchain to enhance the activities corresponding to establishing transactions and monitoring and reporting involved in an additive symbiotic network under the implementation phase. This result is aligned with previous findings regarding the use of blockchain in ISN development (Gonçalves et al., 2022), furthermore, it gives evidence of the use of blockchain technology in enabling an additive symbiotic network.

This study highlights that even though the blockchain may be an enabler for promoting additive symbiotic networks, adopting a new technology may bring new technological implications. Such implications are minimized by adopting a proven blockchain technology that can be deployed in a very short period of time within the infrastructure of a cloud service provider. Nevertheless, a server within a permissioned blockchain must be set up per entity, employees must be trained in the use of the system, and the IT staff must be trained in maintaining the servers' node. On a positive note, interfacing between entities that use the same blockchain technology is streamlined and requires only an effort in the initial setup.

On the other hand, managerial implications also arise with the adoption of a new technologies such as AM and blockchain. Namely, since ISNs aim to promote the exchange of resources among different stakeholders from different value chains or industries, it is critical to put into action proper mechanisms to support the material flow and relationships and manage trust imbalances between stakeholders. Nonprofit organizations and company managers can use the blockchain as a supporting technology for managing transactions and communicating to society their efforts towards sustainability. The use of AM technology to valorize "waste" and residues in an ISN setting creates an additional challenge related to sharing the material characteristic among stakeholders. Most AM processes are sensitive to the input material characteristics, usually, it is required a high degree of purity and standardization of input materials. Using a mixture of materials will imply additional operations for sorting and cleaning before it can be used in the AM process; otherwise, stoppages in the printing process could occur, as well as defective products or of low quality. Blockchain technology can help trace the "waste" and residues flow from their origin until they are used as input material for AM process. Since AM technology is moving to a higher maturity level and the technology costs are decreasing, managers could include this technology in their portfolio of green technologies. They could take advantage of AM technology's reduced needs in terms of built infrastructure but also on the possibility of developing a decentralized additive symbiotic network: the "waste" and residues are not transported through the symbiotic network, but the 3D printer is moved to the place where the "waste" and residues are.

5. Conclusions

The development of additive symbiotic networks, which contribute to promoting additive circular ecosystems, is still in its infancy. Thus, there is a need to find tools that promote the implementation of those kinds of networks. The blockchain technology has proven to have potential applications to enhance the development of such networks. However, adopting such innovative technology should be carefully evaluated since the blockchain technology must meet the requirements for developing additive symbiotic networks.

Using a case study representing an additive symbiotic network under the implementation phase of the industrial symbiosis creation allowed to create a value flow matrix to characterize the flows exchanged within this network. This value flow matrix identified the direct and reciprocal flows, the resources exchanged, and the stakeholders' power distribution. In this additive symbiotic network, the stakeholders corresponding to the network founder - a municipality and the network moderator - a start-up- hold the most power in this network. Furthermore, from the development of the case study, it was possible to conclude that the main activities performed by the stakeholders of this additive symbiotic network corresponded to establishing transactions and monitoring and reporting activities.

Considering that the development of additive symbiotic networks is still beginning and giving the available tools to promote the implementation phase of the industrial symbiosis creation process, disruptive technologies such as blockchain technology have the potential to contribute to the development of such kind of symbiotic networks. Thus, another key finding of this study was the identification of the requirements to adopt the blockchain technology for the development of ISNs within the AM industry, namely: i) need of having a database that should allow to connect all the stakeholders and support the main activities involved an additive symbiotic network in the implementation phase of the industrial symbiosis creation process; ii) the need of having at least two of the stakeholders in the network updating the data in the database; iii) different levels of power within the symbiotic network lead to the inexistence of trust mechanisms between the stakeholders; and also iv) the inexistence of trust between the stakeholders and a third party; v) the data needs to be shared among the stakeholders so they can be able to monitor the status of each transaction and vi) the need to have a unique entity responsible for maintaining the network operationalized. Throughout the development of the case study, a permissioned blockchain was suggested to be adopted to support the development of the activities involved in implementing an additive symbiotic network, namely for establishing transactions and monitoring and reporting.

This study contributes to the literature regarding the development of additive symbiotic networks, providing evidence that there are technical requirements associated with the development of these kinds of networks that are under the implementation phase, such as: i) the need to have a waste material that can be used as a material input for an AM process and ii) the waste producers need to know about the use of the AM technology to incorporate waste from other industries. Additionally, through the development of the case study, it is possible to highlight that the adoption of blockchain technology is expected to have potential benefits regarding the development of additive symbiotic networks, which consequently contribute to enhancing additive circular ecosystems.

Even though this study highlights the role of blockchain technology in the development of ISNs in the AM industry, this study did not apply any economic or numerical analysis that supports the adoption of the technology within this type of setting. Furthermore, within the industrial symbiosis creation process, specifically in the implementation phase, the activity related to the environmental, social and economic impact assessment was not considered. Consequently, a quantitative analysis is suggested for future research work to complement and motivate the qualitative research regarding the use of blockchain technology to enhance symbiotic networks. This would include an environmental, social and economic impact assessment of the networks before and after considering the adoption of the blockchain technology.

Several types of transaction costs can be identified when considering an IS setting, such as: search costs (costs related to locating information about opportunities for exchanges), negotiation costs (costs associated with the negotiation of the terms of the exchanges) and enforcement costs (costs related to the enforcement of the contract). Thus, considering the usual high cost associated with the transactions, there is a need to find technically compatible streams and create and enforce a system of contracts outside the regular purchasing regime. With the adoption of blockchain technology, the stakeholders involved might reduce the transaction costs associated with ISNs. Future research work may compare the transactions' costs of an ISN under the implementation phase before and after adopting the blockchain technology.

Moreover, since trust is one of the most critical challenges in developing ISNs, adopting blockchain technology may affect the relationships between the stakeholders involved in the network. Future research that addresses the impact of adopting the blockchain technology in the inter-organizational relationships that form an ISN will also improve the research to enhance the development of such networks. Additionally, to promote innovative and disruptive technologies such as blockchain technology within these settings, there is a need to develop blockchain-based systems that enhance the development of the ISNs, offering tools for companies to engage in symbiotic relationships.

CRediT authorship contribution statement

Inês A. Ferreira: Conceptualization, Methodology, Investigation, Writing – original draft. **Radu Godina:** Resources, Validation, Writing – review & editing. **António Pinto:** Resources, Validation. **Pedro Pinto:** Validation. **Helena Carvalho:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendices 1 & 2. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cie.2022.108916.

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