Understanding blockchain applications in Industry 4.0: From Information Technology to Manufacturing and Operations Management

Abstract

The current literature regarding blockchain-based applications in the context of Industry 4.0 has rapidly grown during the last decade. However, a systematic literature review that summarizes the main contributions, findings, and implications from a managerial perspective of the blockchain technology adoption in the specific context of Industry 4.0 is still missing. The present article aims to fill this research gap by examining and elaborating on the extant literature to develop a literature-grounded framework (WHY-HOW-WHAT) that helps better understand the issues that blockchain technology can help resolve in the context of Industry 4.0, as well as identify the main features of blockchain-based solutions in various areas of Industry 4.0. Furthermore, the proposed framework is useful to understand how ten Industry 4.0 enabling technologies combine with the blockchain technology to implement efficient and effective blockchain-based solutions in Industry 4.0 settings. Finally, based on this framework we conjecture the trajectories of the evolution of blockchain technology in Industry 4.0 settings, and highlight the relevant research gaps that both academics and practitioners working on this field should address in the near future.

Keywords: Blockchain, Industry 4.0, Supply Chain 4.0, Operations Management, Digital Manufacturing.

1 Introduction

Blockchain technology has been widely studied by computer scientists since its inception in 2008. The problem of guaranteeing trust between peers in a network such as the Internet, without the involvement of a trusted third party was first addressed from a theoretical point of view in 1990 by Haber and Stornetta (1990), who discussed two approaches to sign documents in a trustless network. However, the stepstone and the first practical solution to the trust problem dates to the introduction of bitcoin in 2008, which led to the foundation of the first blockchain algorithm, also known as proof-of-work blockchain (Nakamoto S., 2008). A blockchain is a chain of blocks ordered chronologically, where each block is a container of data, for example, blocks can group a certain number of transactions and some other useful information, such as the ID of the previous block, which is later used to create the chain of blocks. In other words, a newly created block references the previous block by using its block ID, therefore resulting in a chain of blocks. This characteristic of chaining blocks ensures that no block can be modified without the modification of all subsequent blocks. In fact, any modification needs to be approved by the consensus mechanism of blockchains, thus ensuring immutability.

As of today, there are several blockchain architectures such as the Tangle distributed ledger technology (Popov, 2016). whereas in a traditional blockchain architecture all network participants need to be synchronized to the same blockchain after the consensus process is completed, in the Tangle distributed ledger technology all network participants are not always required to synchronize to the same blockchain. Rather, they could store some pieces of the "Blockchain" (Schueffel, 2017). For example, IOTA is a popular blockchain that uses the tangle distributed ledger architecture. Another popular blockchain architecture is the Hyperledger Fabric which was first introduced by the Linux foundation as "Hyperledger project" in 2015 and later renamed as the Hyperledger Fabric (Androulaki et al., 2018). The Hyperledger Fabric is a permissioned or private blockchain architecture, meaning that only authorized network nodes can access such blockchain (IBM, 2022). Ding et al. (2021) suggest that Ethereum and Hyperledger blockchains typically suffer from limited scalability when dealing with massive amounts of data while IOTA blockchain shows rapid verification, stability, and high scalability. However, although IOTA is regarded as a highly scalable blockchain representing the next evolutionary step in blockchain technology, it is, at the same time, more vulnerable than other blockchain implementations since it uses a central server to coordinate transactions (Vafiadis and Taefi, 2019).

The introduction of the first blockchain algorithm in 2008 not only had repercussions on the financial industry, but also paved the way for many blockchain-based applications, one of them being the development of smart contracts over decentralized networks. Smart contracts are programs or pieces of software that are executed on blockchain. In other words, smart contracts are programs that are running on multiple decentralized nodes. The term “Smart contract” was first introduced by Szabo (1997) as follows: “A smart contract is set of promises, specified in digital form, including protocols within which the parties perform on these promises”. However, the first practical implementation of smart contracts dates back to 2013 (Buterin, 2013). Smart contracts enable the implementation of decentralized applications (Dapps), which are applications that are executed on a decentralized network of nodes. Dapps not only allow blockchain technology to flourish, but also allow blockchain technology to be applied on numerous industries. For instance, the Ethereum blockchain can be used to implement food traceability in food supply chains. Decentralized applications have been growing at an extraordinary pace, with estimates stating that the global derived business value from blockchain will reach $3.1 trillion by 2030 (Burke et al., 2018).

In particular, Industry 4.0 has been one relevant field of application of blockchain technology. The fourth industrial revolution, commonly known as Industry 4.0, was initiated in Germany in 2011 and further popularized by the German government in 2013 through the “high-tech strategy 2020” action plan (Lasi et al., 2014; Vogel-Heuser and Hess, 2016). Since then, Industry 4.0 has grown rapidly worldwide, with the goal of addressing the complete transformation from machine powered manufacturing to smart manufacturing, thus allowing machines to execute production without the need of human intervention (Algabroun et al., 2022). In other words, under the Industry 4.0 paradigm the idea is to enable machines to autonomously perform decision making and problem-solving tasks inside the traditional manufacturing and operations processes (Oztemel and Gursev, 2020). Accordingly, to accomplish this, it is necessary to guarantee interconnection between machines, decentralization, and information transparency, which can indeed be implemented by using the blockchain technology.

The current literature regarding blockchain-based applications in the context of Industry 4.0 has rapidly grown during the last decade, with the intent to unravel a number of critical aspects such as advantages, disadvantages and the drivers behind the adoption of blockchain technology (Leng et al., 2020a; Bhatt et al., 2021; Leng et al., 2021; Li et al., 2021; Majeed et al., 2021; Benz et al., 2022; Leng et al., 2022c, among others). There are also some excellent review studies summarizing the state-of-the-art of blockchain technology challenges (e.g., Lu, 2019). However, a systematic literature review that summarizes the main contributions, findings, and implications, *from a managerial perspective*, of the blockchain technology adoption in the context of Industry 4.0 is surprisingly still missing. The present article aims to fill this research gap by examining and elaborating on the extant literature to develop a literature-grounded framework (WHY-HOW-WHAT) that helps better understand the issues that blockchain technology can help resolve in the context of Industry 4.0, as well as identify the main features of blockchain-based solutions in various areas of Industry 4.0. Furthermore, the proposed framework is useful to understand how ten Industry 4.0 enabling technologies combine with the blockchain technology to implement efficient and effective blockchain-based solutions in Industry 4.0 settings. Finally, based on this framework we conjecture the trajectories of the evolution of blockchain technology in Industry 4.0 settings, and highlight the relevant research gaps that both academics and practitioners working on this field should address in the near future.

The remainder of the paper is organized as follows. Section 2 presents the methodology utilized for the systematic literature review. Section 3 presents the analysis of the extant literature on blockchain-based applications in Industry 4.0 categorized by type of such applications. Section 4 proposes a framework, which is based on the current literature, to better understand the issues, drivers and solutions related to the adoption of blockchain in the context of Industry 4.0. Finally, Section 5, in light of the proposed framework, provides conclusions and research gaps that should be addressed by scholars in the near future.

2 Methodology

The present article examines the main contributions, findings, and implications of blockchain-based applications in Industry 4.0 settings, in order to develop a framework which helps better understand blockchain-based applications in the context of Industry 4.0. To accomplish this task, all published articles including both the term "Blockchain", and the term "Industry 4.0" available in (Elsevier-owned) Scopus repository were selected as of February 2022. This search resulted in a total of 569 articles. However, after a careful examination of all these articles, we noted that some of them focused only on blockchain technology just mentioning Industry 4.0 applications, or vice versa. As a result, the total number of articles considered in this research was narrowed down to 224 articles, which were actually analyzing both blockchain and Industry 4.0. Broadly speaking, the focus of all considered articles was either to propose blockchain-based solutions for Industry 4.0 problems, or to present useful blockchain frameworks for solving specific Industry 4.0 problems. Even though selected articles were published in 153 different journals, 33 journals accounted for approximately 50% of the total number of articles considered in this research. As reported in our reference section, the highest number of occurrences refer to journals focusing on manufacturing and operations, information technology, and sustainability. We then analyzed these 224 articles to define the state-of-the-art of blockchain applications in Industry 4.0 and build the above-mentioned framework. Figure 1 reports a PRISMA flowchart that shows the various phases of this systematic literature review. The next section, instead, presents the outcome of this literature review, whereas section 4 discusses the framework.

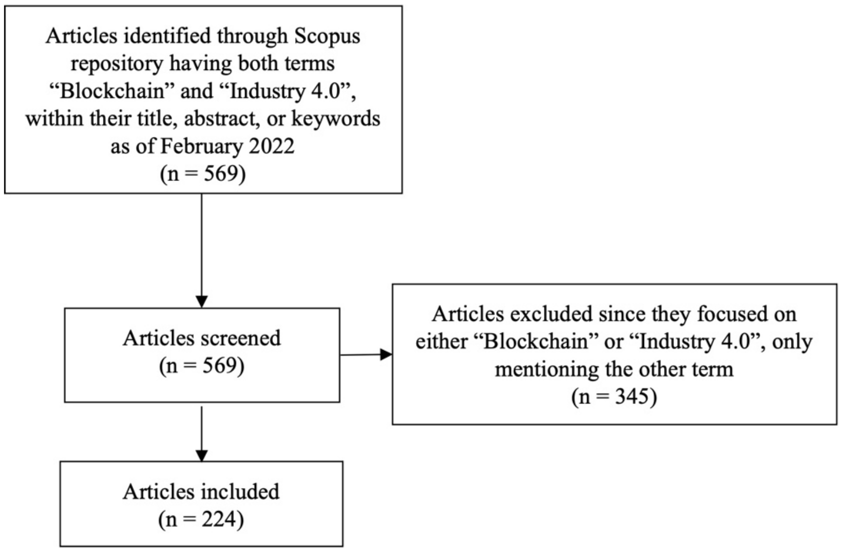

Figure 1 - PRISMA flowchart

3 Blockchain technology and Industry 4.0

3.1 General background

Some experts predict a slow and limited but steady spread and use of blockchain technology, while others compare the current blockchain situation to the internet in the early 1990s (Mittal et al., 2019; Leng et al., 2020a; Lohmer and Lasch, 2020; Unny and Lal, 2020; Hopkins, 2021, Sundarakani et al., 2021). This can be further explained by the fact that the blockchain technology not only enables infrastructural changes, but also accelerates substantial organizational changes. The extant literature suggests that many companies find a massive gap in the understanding of blockchain technology, lack of experienced consultants, poor regulatory provisions, and high costs when implementing blockchain-based systems (Al Barghuthi et al., 2019; Etemadi et al., 2021; Vu et al., 2021). Nevertheless, research on blockchain technology is growing at an exponential pace (Bhatt et al., 2021; Benz et al., 2022). Moreover, Majeed et al. (2021) suggest that blockchain technology should be crucial in our future data-driven world, thus ensuring traceability and immutability of data exchange between data providers and data consumers (Tan et al., 2021). In this regard, organizational resilience can be seen as a key enabler for the adoption of blockchain technology (Rodríguez-Espíndola et al., 2022). In particular, the blockchain technology is increasingly used when dealing with Industry 4.0 issues, such as reducing the risk of data loss and tampering, improving reputation systems, as well as ensuring data sharing, decentralization, and transparency (Yan et al., 2017; Jo and Park, 2020; Aoun et al., 2021; Hassan et al., 2021; Leng et al., 2021), as explained in the following examples.

Blockchain is showing great potential in business process management systems (e.g., production and operations management systems) by implementing systems that are collaborative, secure, and cost-effective, as well as providing a trustful infrastructure which could significantly reduce data processing delays (Viriyasitavat et al., 2019; Viriyasitavat et al., 2019; Chang, 2020; Viriyasitavat, 2020; Rahman et al., 2021; Viriyasitavat et al., 2022). Centralized databases traditionally have several problems when there are multiple autonomous entities actively participating in data editing. Data integrity is often compromised in traditional database systems. Moreover, centralized databases are considered as central points of failure and cause bottlenecks when information systems are overwhelmed by multiple requests. Blockchain helps overcome most of previously mentioned issues by providing a trustful, decentralized, and secure architecture (Fernandez-Carames and Fraga-Lamas, 2019). For example, Garrocho et al. (2020) proposes a blockchain-based system that enables machine-to-machine communications in the mining industry, by deploying such system directly on industrial devices, and thus eliminating delays generated by the presence of intermediary devices. In the same vein, blockchain-enabled cloud manufacturing systems overcome traditional cloud manufacturing systems, which always rely on the presence of a trusted third party. In fact, blockchain-enabled cloud manufacturing systems can deliver trustful on-demand manufacturing services from providers to users thanks to the use of smart contracts, ensuring the reliability of cloud manufacturing services without the need of a trusted third party (Adhikari and Winslett, 2019; Aghamohammadzadeh and Valilai, 2020; Kaynak et al., 2020; Zhu et al., 2020; Vatankhah Barenji, 2021).

Blockchains significantly reduce information asymmetry between various actors of the supply chain (Ada et al., 2021; Pérez et al., 2022). For instance, blockchains enable the transformation of the automotive industry from a non-collaborative to an inclusive organizational structure, namely in an inclusive organizational structure all actors could easily participate in decisional processes thanks to the higher transparency and availability of information (Fraga-Lamas and Fernández-Caramés, 2019; Wang et al., 2021). In this regard, blockchain technology could remove barriers of entry in various markets, therefore enabling independent actors to compete with well-established competitors. For instance, independent manufacturers could rely on blockchain technology to ensure an immutable reputation, ease of transaction with final consumers, and eliminate high intermediary costs. As a result, blockchain use could significantly boost the value of products by providing higher transparency of communications. Moreover, by removing central intermediaries in supply chains, blockchain technology can favor the shift toward a more sustainable and circular business models (Wang et al., 2020; Soni et al., 2021).

In light of all these characteristics, the blockchain technology is seen as an enabling driver of Industry 4.0 (Lu, 2021). In the next subsections, we discuss in greater detail the contribution, findings, and implications of the extant literature on the blockchain-Industry 4.0 combo, by examining in turn manufacturing 4.0 and supply chain 4.0, which represent the main areas of applications within Industry 4.0.

3.2 Blockchain technology and Manufacturing 4.0

Manufacturing 4.0, also known as digital manufacturing or smart manufacturing, relies on smart machines to implement autonomous decision making in various processes. As a result, manufacturers could transfer ownership, access, and responsibility to a group of self-governed machines (Hassan et al., 2020). The machine autonomy is realized by using cheap sensors that collect raw data from machines. Subsequently, such data are processed by smart devices without the intervention of humans, thus resulting in high quality data. Deloitte and MHI research estimate the presence of almost 1 trillion sensors by 2022 and up to 10 trillion sensors by 2030 across manufacturing industries (Gupta, 2021). Such high number of sensors generates massive amounts of data on a daily or even hourly basis. This implies the necessity of maintaining the privacy and secrecy of collected data at a firm level. Otherwise, the risk of data tampering, data loss, or unauthorized access might compromise important intellectual properties. The security and privacy issues in digital manufacturing systems are not only caused by external attackers. Indeed, about 60% of the attacks are conducted by employees and contractors to steal intellectual property (Sturm et al., 2017). For these reasons blockchain technology is gaining more attention in the context of digital manufacturing, as it removes single points of failure, therefore providing resilient systems (Huang et al., 2019; Elmamy et al., 2020; Leng et al., 2022b).

In this regard blockchain-based solutions vary from hybrid to fully blockchain-enabled systems. That is, blockchain hybrid systems combine blockchain with other technologies, which are referred as the enabling technologies in the proposed framework, thus resulting in robust and secure systems (Hameed et al., 2022). For instance, both Petrali et al. (2018) and Sittón-Candanedo (2020) suggest combining edge computing with blockchain to ensure the privacy of huge manufacturing data, as well as decentralizing factory automation systems on a large scale, which facilitate distributed real-time control and scalable data processing. On the one hand, edge computing ensures low latency therefore optimizing the network usage, on the other hand blockchain provides data integrity, trust, agreement automation, reliability, and ultimately security (Kumar et al., 2020). In the same vein, both Arachchige et al. (2020) and Demertzis et al. (2021) suggest combining federated learning techniques with Ethereum blockchain and Hyperledger Fabric respectively, to ensure privacy, trustworthiness, and secrecy of industrial data. Moreover, coupling blockchain technology with low consumption sensors is also underscored in extant literature to result in power efficient, secure, and trustworthy systems (Sodhro et al., 2020; Sunny el al., 2020; Kim et al., 2021). Such systems also provide a platform for collaboration among entities while maintaining the integrity of critical and sensitive data (Sodhro et al., 2020; Sunny el al., 2020; Kim et al., 2021). Finally, Bhattacharjee el al. (2020) suggests combining clustering mechanisms with blockchain technology to achieve scalable and secure manufacturing systems. By doing so, blockchain offers reliable access and secure data management, as well as safe sharing of industrial data in the field of cyber physical systems (Lee et al., 2019; Yu et al., 2020; Suvarna et al., 2021).

Looking at blockchain-based applications in the context of maintenance, blockchain technology could ensure traceability and control of maintenance interventions. It favors the replacement of manual tasks, which are often paper-based, by means of smart contracts and automatic data collection, as well as significantly improving the transparency of maintenance operations since all stakeholders are able to visualize performed maintenance operations and, at the same time, are forced to correctly perform maintenance operations due to the fact that all maintenance operations are recorded on blockchain (Stodt et al., 2019; Welte et al., 2020; Aheleroff et al. 2021). Furthermore, blockchain technology can ensure the safety and security of remote maintenance interventions over sensor-equipped machinery, which are often prone to software vulnerabilities. In this case, blockchain technology ensures the integrity of software updates and that no malicious copy of the software is being downloaded (Dreyer et al., 2021). Moreover, blockchain technology coupled with the well-known fog computing paradigm can significantly improve accountability, traceability, and transparency of all physical maintenance interventions done by technicians for each smart device in the production process (Seitz et al., 2018; Barenji et al., 2021). In this regard, Lallas et al. (2019) combine fog computing, cloud computing, and blockchain technology for real time machine condition monitoring and fault prediction. Barenji et al. (2021) propose a blockchain-enabled fog computing-based collaborative design and manufacturing platform that also includes the view of customers. In the same vein, the combination of AI and blockchain capabilities can result in smart maintenance systems, which can monitor system conditions, diagnose problems, and request the replenishment of supplies. For instance, blockchain could offer reliable data storage architecture, meanwhile AI capabilities could offer self-learning abilities through the use of reinforcement learning and not necessarily supervised learning algorithms (Abdulrahman, 2022). When blockchain and AI technologies are used in combination with large datasets that originate from machines during production, manufacturers gain a competitive advantage in the operational control and improve the efficiency of their production systems (Demertzis et al., 2020). For these reasons, the combination of blockchain and AI could give birth to "Decentralized AI", which allows the presence of decentralized nodes to compute AI algorithms in parallel without compromising the trustworthiness of such systems (Chavali et al., 2020).

Blockchain technology shares digital twins' information among all stakeholders, such as final consumers and manufacturers, and guarantees a tamper-proof platform for the creation of digital twins (Guo et al., 2020; Hasan et al., 2020). In this regard, blockchain significantly optimize digital twin systems by decentralizing and creating a tamper-proof environment for collaborative planning (Leng et al., 2020b). Moreover, blockchain-enabled digital twins do not have a single point of failure, rather they are distributed and decentralized. For such reason, blockchain-enabled digital twins are more resilient to cyber-attacks compared to centralized digital twins (Sahal et al., 2021). Blockchain can also operate together with traditional systems in a complementary manner, that is by offering secure and fast certification systems for manufacturing data (Softic et al., 2021; Costa et al., 2022). For instance, blockchain technology can store the digital entity or token of a physical asset, ensuring that only authorized actors will be able to access the digital information of such physical asset (Zuo, 2021). Recently, Putz et al. (2021) implemented an Ethereum Dapp “EtherTwin” that can ensure a secure fine-grained access control of digital twins’ information by using the Ethereum blockchain coupled with encrypted off-chain data storage. Similarly, Lin et al (2018) and Deebak and AL-Turjman (2021) propose access control blockchain-based systems to ensure the security and privacy of various Industry 4.0 applications. Furthermore, Mazzei et al. (2022) proposed an industrial Internet of Things tokenizer, which acquires data coming from modern and legacy industrial machines to create the digital twin or token of a physical industrial asset using the Ethereum blockchain.

Blockchain technology has paved the way to the development of Non-Fungible Tokens (NFTs) which can be seen as the property certificate of a particular asset, such as physical or digital asset, that cannot be counterfeited (Carayannis et al., 2022). As a result, NFTs publish and register valuable assets of businesses, as well as making such assets publicly available for bidding or auditing operations. In the same vein, blockchain transparency significantly improves the auditing process of companies, that is by simplifying the process of finding and tracking documents, as well as providing evidence for legal cases due to blockchain immutability (Rastogi et al., 2022; Lin et al., 2022).

It is expected that most paper-based certificates of employees’ competences, educational and professional background in manufacturing and other business areas could be replaced by blockchain-based certificates (Lahbib et al., 2019; Hernandez-de-Menendez et al., 2020). This may be explained by the fact that Dapps allow to preserve the integrity and authenticity of sensitive documents such as contracts, proof of ownership and patents (Son and Kim, 2019; Zhang et al., 2020). Moreover, Blockchain based certificates are tamper-proof and easily verifiable by employers thanks to their secure and distributed nature (Hennebert and Barrios, 2020). For instance, Srivastava et al. (2022) proposes a blockchain technology-based recruitment management system that can be used by hiring companies to efficiently verify candidates’ competencies, thus implementing a decentralized human resource management system that is cost-effective and trustworthy. Blockchain technology empowers digital credentialing by creating a record of individual certifications, which allows students to gain internationally transferable certifications, therefore assuring the quality and integrity of educational courses (Pannen, 2021).

Blockchain technology can also have a substantial impact on resolving conflicts that may emerge along manufacturing processes. To illustrate, the manufacturing head of department may be interested in increasing production even at the risk of reducing the safety of her/his workers. Tampering the health records of their workers can be simply done in presence of centralized databases. In contrast, an immutable Dapp can regularly record the health data related to each worker, and ensure the occupational health and safety of each worker. In other words, by means of wearable devices and blockchain technology the health and performance of each worker can be recorded and monitored with a lower risk of data tampering (Torrecilla-García et al., 2020). As suggested by Hunhevicz and Hall (2020), a private permissionless blockchain can also be used for this issue. Blockchain immutability and traceability allows adherence to human rights, such as fair and safe working conditions, since recorded data cannot be later modified (Eashwar and Chawla, 2021; Hong et al., 2021; Razak et al., 2021; Huo et al., 2022). More recently, Rathee et al. (2021) proposed an industrial Internet of Things framework that ensures secrecy and transparency of each worker or product related data, by recording data on the blockchain and thus avoiding data alteration.

Blockchain technology enables smart machines to become autonomous actors by providing a trustful infrastructure as well as a reliable infrastructure for automated agreements (Mohamed and Al-Jaroodi, 2019; Miehle et al., 2019). Smart machines are enabled to perform automated ordering and settlement, execute and record agreements, therefore becoming self-determined market actors (Zheng et al., 2021). Even though current blockchains suffer from high transaction costs, blockchain technology and smart contracts show promising potential for decentralized production control, handling authentication, verification, and inter-organizational transactions (Laabs and Dukanović, 2021). In particular, hybrid blockchain systems could have great potential in future due to their capabilities of achieving short runtimes and lower transaction costs compared to fully blockchain-based systems, and, at the same time, ensuring blockchain capabilities such as decentralization and transparency (Garrocho et al., 2021). Kwok and Koh (2020) suggest that blockchain technology can be seen as a digital catalyst for manufacturing improvements in two main areas: process transformation and system integration. With regard to the first area, it is highlighted how the blockchain technology can directly improve manufacturing and operations processes. The second area, instead, examines how blockchain technology is integrated with other emergent manufacturing technologies to shape the manufacturing ecosystem of Industry 4.0. In this respect, Kwok and Koh (2020) suggest that, in spite of its early lifecycle stage, the blockchain technology is already showing great potential along both directions.

3.3 Blockchain technology and Supply Chain 4.0

One emerging tenet in the literature is that the blockchain technology is also rapidly changing supply chain management systems by improving product traceability, documenting each transaction, and creating an immutable history of transactions, as well as increasing the efficiency and security of delivery processes (Bodkhe et al., 2020; Grecuccio et al., 2020; Mehta et al., 2020; Muzylyov and Shramenko, 2020; Rodrigues et al., 2021; Raimundo and Rosário, 2022). There is unanimous agreement in the literature that blockchain technology increases supply chain transparency (Gong et al., 2020; Kurnia et al., 2020; Popkova and Sergi, 2020; Venkatesh et al., 2020; Wang et al., 2020; Živić, 2020; Bedi et al., 2021; Benzidia et al., 2021; Dietrich et al., 2021; Menon and Jain, 2021; Reno et al., 2021; Chen et al., 2022a; Chen et al., 2022b; Wamba and Queiroz, 2022). Nyugen et al. (2021) report that the blockchain technology has a direct link with the term traceability, by analyzing 3858 scientific articles recovered from Science Direct, Scopus and IEEE repositories using a topic modeling approach. Moreover, blockchain topic could be seen as the most recent topic in research compared to digital twins and industrial internet of things (Nyugen et al., 2021).

Barata et al. (2020) report the usefulness of coupling blockchain technology with digital twins to record and ensure full transparency in the paper pulp supply chain. Moreover, blockchain transparency shows promising potential in providing the actual amounts of produced and traded cocoa in the complex cocoa supply chain where various farmers, collectors, agro-industry firms, and exporters are involved (Iswari et al., 2019). Blockchain transparency makes it easier to verify products' history by each actor along the supply chain, thus certifying each component from raw materials to the final product, as well as protecting consumer rights (Ada et al., 2021). Khan et al. (2020) combines the use of blockchain technology with advanced deep learning techniques to provide traceability and transparency of food product information from suppliers to end users. For example, blockchain-based systems significantly improve traceability of spare parts and provide a reliable information sharing mechanism, as well as enhancing information sharing and security (Zhao et al., 2019; Ho et al., 2021; Latino et al., 2022). Moreover, blockchain transparency significantly increases trust between various actors along the supply chain, thereby reducing frauds, lack of information, and missing information interchange (Fernández-Caramés et al., 2019; Longo et al., 2019; Maryniak et al., 2021).

The traceability of all raw materials used to create final products is sometimes a legal requirement in certain process industries such as food and pharmaceutical industries. For these reasons, blockchain technology is showing great potential for developing accurate tracking systems capable of offering real-time traceability of food products from farms to forks, thus ensuring food safety (Ivanov et al., 2019; Casino et al., 2020; Helo and Shamsuzzoha, 2020; Galanakis et al., 2021; Kayikci et al., 2022; Latino et al., 2022). For instance, the company Bumble Bee Foods traced yellowfin tuna from origins to the end sale point by using blockchain technology in 2017. Specifically, each actor along the supply chain could access the complete journey and processing history of the yellowfin tuna by scanning the QR code on the product package. As a result, end users could know detailed information about products such as point of capture, as well as providing transparent processing cycles, which ensured food authenticity, freshness, and safety (Kouhizadeh et al., 2020). Due its traceability features, blockchain technology can be used as an effective anti-counterfeiting mechanism, enhanced by machine learning and fuzzy logic-based systems. In this context, for instance, Shahbazi and Byun (2021) propose a useful blockchain machine learning-based system for food traceability. However, according to Kawaguchi (2019) when supply chains get more complicated involving various actors and activities, blockchain technology has limited scalability when dealing with such huge amount of data. Kawaguchi (2019) suggests that a hybrid solution that combines blockchain technology with distributed storage services seems as a more concrete solution to current issues.

Product lifecycle systems are traditionally implemented in a centralized manner by software vendors, which hinders information sharing and increases data fragmentation between cooperating business partners. The same applies to the case of enterprise resource planning (ERP) systems, which store information that comes from multiple business areas within a firm in a centralized manner. However, given the globalized nature of many supply chains, it is often necessary to share such information with other business partners in a trusted and secure environment (Aguilar-Ramirez et al., 2022). Blockchain-based systems could connect all business partners in a secure and open environment, thus mitigating trust issues in collaborative environments, managing contracts, and ensuring continuous control of the transmitted financial and sensitive data (Belhi et al., 2020; Liu el al., 2020; Stepanov, 2021; Aguilar-Ramirez et al., 2022). For instance, an important aspect in the steel industry is to share the correct data of steel alloys such as steel sheets' thickness between all involved actors to ensure an accurate processing of steel alloys. However, recorded data is often not exchanged between various business partners due to the lack of trustworthy means of communication. Both Frey et al. (2019) and Datta and Bhattacharjee (2021) propose blockchain-based systems, which ensure secure data exchange between all stakeholders, as well as preventing data tampering. Blockchain technology can guarantee interoperability of supply chain data by setting a standard format between various actors along the supply chain (Kumar et al., 2022). Popular blockchains that provide an interoperable infrastructure include Cosmos and Polkadot blockchains (Schulz and Freund, 2019). Recently, Rodríguez-Espíndola et al. (2022) shows that blockchain technology enhances data fusion processes, which include different data sources and formats, therefore resulting in an increased capability to draw knowledge from our data, as well as increasing the transparency and enhancing communications and data sharing among all stakeholders (Bamakan et al., 2021). For instance, Nasu et al. (2021) propose a data sharing solution that can exchange confidential data between various actors in the supply chain without the need of disclosing the data by combining blockchain technology with encryption techniques.

Supply chains present numerous inter-dependencies between its various actors, thus complicating decision-making processes due to the difficulty of tracking all transactions. However, the decision-making process could be significantly improved by combining blockchain technology with multi-agent systems, which would further enhance the authenticity and immutability of data (Pinheiro et al., 2019). Moreover, blockchain provides decentralized consensus mechanisms, which transform traditional centralized supply chain processes, such as (re)supply and dispatching processes into collaborative multi-agent systems, thus involving all actors in their relative supply chain networks (Leng et al., 2022a). For instance, many human interventions occur along the textile supply chain due to the involvement of a plethora people in the production process and various raw materials during the manufacturing phase. Blockchain-enabled supply chains can be used to document and track every step a particular garment has gone through, therefore increasing supply chain visibility, as well as significantly improving product fault traceability (Abreu et al., 2021; Faridi et al., 2021). Blockchain technology establishes a distributed data management system to support trading services of a multi-party global apparel business network in the textile industry (Pal and Yasar, 2020). Moreover, blockchain significantly improves supply chain resilience and reduces the waiting times of supply chain nodes. In this regard, Suhail et al. (2020) suggests using IOTA blockchain for supply chain related problems due to its rapid processing times and improved transparency (Lohmer et al., 2020; Ada et al., 2021; Variale et al., 2021). Blockchain technology also enables smart purchasing processes along supply chains by providing information synchronization, and real-time tracking among all stakeholders (Zheng et al., 2021; Rane and Narvel, 2022). In this regard, blockchain technology removes expensive intermediary and operational costs and replace them with a trustful structure for cross border transactions (Kimani et al., 2020). Blockchain could be used by small and medium companies to implement supply processes having low cost and effective anti-counterfeiting features (Ma et al., 2020).

Blockchain technology can also support the digitalization of the process of shipping goods, where there are various actors involved in shipping processes and a great amount of paperwork to be filled (Latino et al., 2022). For instance, DHL estimates that up to 10% of its lading activities data contains incorrect data, which may give cause to lawsuits (Issaoui et al., 2019; Kusi-Sarpong et al., 2022). To address such issues, IBM and Maersk formed a partnership in 2017 to automate shipping processes by using blockchain technology, which would digitally store and track the documents of shipping containers. In other words, all actors along the supply chain could access information without duplication errors or delays, by leveraging the distributed, transparent, and secure nature of the blockchain technology (Tang and Veelenturf, 2019). In the same vein, Walmart was granted a patent for its logistics process, which combines delivery drones with blockchain technology into shipping and sea transportation processes. By doing so, Walmart was able to reduce the time of its information tracking processes from 7 days to few seconds (Issaoui et al., 2019; Choi et al., 2022). Blockchain together with deep learning algorithms can also better help design energy-efficient networked logistics processes that involve all business partners and are also self-learning from big logistics data (Yang et al., 2023).

Similarly, blockchain is showing great potential for addressing various challenges when implementing smart transportation systems, such as resolving trust issues, as well as providing secure interactions between autonomous agents, which are often distributed in a decentralized manner (Kapitonov et al., 2018; Majeed et al., 2021). For instance, traditional systems are based on centralized architectures in urban transportation systems, therefore having a single point of failure. Blockchain technology makes the communications of smart transportation systems safe and secure, due to blockchain transparency, traceability, immutability, and reliability, as well as mitigating trust issues in urban mobility systems (Gupta et al., 2020; Niya et al., 2020; Abbas et al., 2021; Chauhan et al., 2021).

Blockchain transparency and traceability increases the sustainability of production processes by significantly reducing frauds, paperwork delays, and wastes, as well as identifying shipping problems faster and enhancing the efficiency of supply chains (Khanfar et al., 2021; Sunmola, 2021; Sunmola et al., 2021).

Blockchain together with chemical signatures that use carbon dots bring a highly valid and sustainable traceability alternative to traditional technologies for tracking, such as QR codes, RFID, and NFC. In this regard, Leng et al. (2019) proposes *Makerchain*, a blockchain utilizing chemical signatures to ensure product traceability in the context of social manufacturing. Additionally, Kennedy et al. (2017) propose another useful example of chemical signatures in the context of additive manufacturing. Mukherjee et al. (2020) further suggests that blockchain-enabled supply chains have far more potential to bring sustainability in supply chains than traditional supply chains due to increased automation, visibility, and integration. For instance, Fu et al. (2018) propose a great example of using blockchain technology to reduce carbon emissions in clothing production processes. Blockchain positively affects circular economy practices such as circular procurement, circular design, recycling, and remanufacturing (Asante et al., 2021; Khan el al., 2021). Moreover, blockchain is capable of promoting green behavior among consumers by applying blockchain incentives and tokenization mechanisms (Esmaeilian et al., 2020). Glavanits (2020) suggests that blockchain technology meets all sustainable development goals.

Blockchain technology can be successfully employed in food supply chains to achieve increased visibility among all actors along the entire supply chain (Casino et al., 2019; Liu et al., 2021). Survey results show that blockchain technology increases the added value to logistics and supply chain processes compared to other Industry 4.0 technologies (Markov and Vitliemov, 2020). Moreover, the use of blockchain technology allows firms to promote their core values, such as sustainable materials, recycled plastic use, and authentic materials along the supply chain. In other words, Italian, organic or Halal products can be easily verified by using a Dapp (Ali et al., 2021), thus positively impacting customer relationships (Stanisławski and Szymonik, 2021). According to Lezoche et al. (2020) blockchain technology increases customer satisfaction by automating products safety and quality certifications, as well as empowering customers, who become in control of all the information related to their purchased products (Latino et al., 2022). Blockchain-enabled supply chains easily detect tampered or counterfeited products, thus certifying product quality and recording product authenticity. For instance, blockchain technology has been shown to limit individual tampering of certified sustainable palm oil (CSPO), which is characterized by a huge number of small-medium enterprises along the supply chain, thus ensuring the traceability of palm oil lifecycle (Lim et al., 2021). In the same vein, IBM food trust uses blockchain technology to implement transparency from farmers to final consumers by using a tamper resistant blockchain.

Blockchain technology could contribute solving the longstanding problem of digitalizing various supply chain processes in the construction industry, such as real estate management, the monitoring of carbon emissions, and the recycling process of construction wastes (Perera et al., 2020; Balasubramanian et al., 2021; Elghaish et al., 2021; Teisserenc and Sepasgozar, 2021b; Ullah and Al-Turjman, 2021). Blockchain transparent nature and immutability adds value to communications and information exchange between various actors of construction supply chains (Yavu et al., 2021). For instance, construction projects, which involve public institutions, often suffer from frauds and corruption, as a result leading to low-quality, high-cost, and time-consuming construction projects. For these reasons, blockchain can come to rescue construction projects providing transparency of used materials, as well as documenting the correct expenditure of public funds. In other words, all involved actors become more accountable for their actions due to the higher transparency of blockchain-enabled projects (Shinde et al., 2020). Furthermore, blockchain technology can convert construction projects from simple buildings to interactive buildings, therefore linking construction projects to cities which they occupy, that is due to the higher availability of information regarding such projects (Duran et al., 2021).

Interestingly, blockchain technology can also be useful for managing supply chain operations in the energy industry. In fact, even though the transaction time of blockchain has been regarded as unsuitable for *real-time* operations in the energy industry (Ledwaba et al., 2019, Ledwaba et al., 2021), with the rapid development of smart grids during the last years in the energy industry, blockchain hybrid systems are showing great potential for securing transactions during the trade of energy surpluses through smart contracts (Puri et al., 2020; Borowski, 2021; Son et al., 2021). Blockchain technology can provide full trustworthiness and fairness in smart grids between involved decentralized nodes during the processes of collecting and distributing energy (Li et al., 2020a; Li et al., 2020b; Guan et al., 2021). In other words, smart grids, which have a decentralized structure with a bi-directional flow of energy and data, need robustness and stability to avoid single point of failure. This can be obtained by implementing blockchain-enabled smart grids (Guan et al., 2021). Furthermore, blockchain transparency can be used for proving and tracing all transactions in smart grids, therefore providing an efficient interconnection mechanism between all the stakeholders of smart grids (Alcaraz et al., 2020). In this regard, by combining the federated learning paradigm with the blockchain technology, Otoum et al. (2022) propose blockchain-enabled energy-trading framework which allows energy services to be distributed in an autonomous manner without the involvement of a trusted third party. In the same vein, the use of blockchain in smart grids allows prosumers to purchase and sell energy by directly transacting over the blockchain in real-time, thus converting traditional centralized energy systems into decentralized systems that securely handle real-time operations (Sikorski et al., 2017, Hossain et al., 2020; Kumari et al., 2021, Sreeramulu Mahesh et al., 2021). It is also noteworthy that blockchain can be used for reducing the carbon emission of energy systems, that is by implementing a trustworthy reputation system that shows the performance and commitment of energy network peers towards carbon emission reduction (Khaqqi et al., 2018). In this regard, blockchain provides a reliable and trustful architecture for implementing renewable energy certifications, which can be used by all stakeholders to verify the sustainability of their energy sources (Teng et al., 2021). The use of blockchain in this case ensures immutability of data and trust between network peers, as well as preventing data loss (Le et al., 2022).

Finally, blockchain technology is extremely relevant in pharmaceutical industry supply chains nowadays. The drug authenticity and adherence to the health standards are vital to save the lives of people. Unfortunately, drug tampering is a widely common issue worldwide. For instance, about 80 people received fraudulent doses in Mexico, and authorities recovered vials likely containing an antiwrinkle treatment in Poland during the recent COVID-19 vaccine distribution (Hopkins and Córdoba, 2021). More generally, drug counterfeiting often arises due to the centralized nature of national and international health agencies, which frequently suffer from corruption-related issues. Tampered drugs not only affect people's health but also, they cause financial losses to both final consumers and drug producers. Given the fact that there are many parties involved in the process of drug distribution from the producer to the final distributer, the healthcare industry needs platforms that are resistant to the risk of tampering and able to prevent frauds, that is to solve the issue of trust in the drug supply chains. In other words, counterfeited drugs can be generated at any distribution phase along drug supply chains. For this reason, the use of blockchain in the drug and health industry becomes crucial nowadays and can be used to address the counterfeiting problem by introducing accountability and transparency to drug supply chains (Chiacchio et al., 2019; Paul et al., 2021). In this regard, Chen et al. (2020) proposes an effective way to mitigate such issues by implementing a traceable management system combining blockchain with IoT in the context of drug anti-counterfeiting. Also, Raxit et al. (2021) uses the Hyperledger blockchain to ensure a transparent drug supply chain, which allows manufacturers, distributors, pharmacies, and patients to easily access drug information. Moreover, Dapps can be fundamental for a fair vaccine dispersion by ensuring that all stakeholders have complete access to supply chain data from producers to final consumers on a publicly available system (Safraz et al., 2022). Furthermore, blockchains improve the identification of contamination sources in blood donation supply chains, thus significantly reducing the spread of viruses, such as HIV (Çağlıyangil et al., 2020).

4 The blockchain pyramid of applications in Industry 4.0: WHY, HOW, WHAT?

This section builds upon the insights and evidence provided by the extant literature examined above to conceptualize and introduce a framework useful to understand current and future issues regarding the applications of blockchain technology in the context of Industry 4.0, as well as highlight the main features of current blockchain-based solutions in various areas of Industry 4.0. Further, the proposed framework, reported in Figure 2, is useful to identify enabling technologies, which are combined with blockchain technology, to implement efficient and effective blockchain-based solutions. Specifically, the proposed framework is essentially built by answering ***why***, ***what*****,** and ***how*** questions. That is, prior to identifying how blockchain based solutions are implemented, the presented framework starts from the extant literature to answer ***why*** blockchain technology is used, in combination with enabling technologies, in the context of Industry 4.0, and ***what*** are the features of solutions proposed in the literature to solve Industry 4.0-related issues. Subsequently, the proposed framework identifies ***how*** blockchain-based solutions are implemented, thus pointing out which technologies are being coupled with blockchain technology in the current literature in order to implement blockchain-based systems.

The logic underlying Figure 2 can be summarized into two main parts. First, the oval shape underscores the main problems of Industry 4.0 that can be resolved or at least mitigated by using blockchain technology. Therefore, this part helps explain why blockchain is utilized in the context of Industry 4.0. Such features were repeatedly highlighted by the literature in Section 3, therefore indicating a need to resolve them. Second, the pyramid describes how blockchain technology is being utilized in the literature and what the features of blockchain-based solutions are. As a result, the pyramid can be further divided into two main parts. First, the features of blockchain-based solutions, which are reported on the top layer of the pyramid. Second, blockchain architectures and enabling technologies, which are illustrated at the two bottom layers of the pyramid in Figure 2. The very bottom layer of the pyramid reports some examples of blockchain technologies that are programmable, such as Ethereum, IOTA, Hyperledger Fabric and Cosmos. Programmable blockchains are the most frequently used in Industry 4.0, due to the possibility of implementing Dapps, which could help resolve numerous issues identified above in the context of Industry 4.0. The middle layer of the pyramid describes the enabling technologies of blockchain applications. In fact, most of the current literature combines blockchain technology with ten main technologies to implement systems that are capable of resolving industry 4.0 problems.

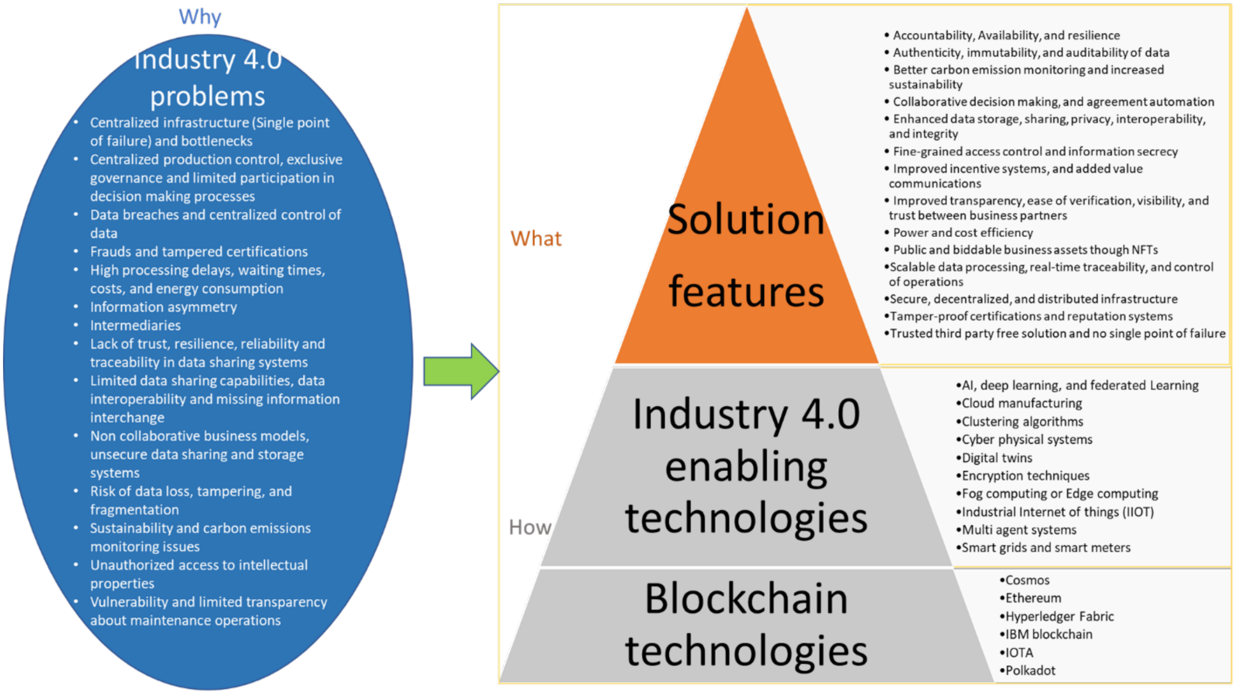

Figure 2 - The blockchain pyramid of applications in Industry 4.0

4.1 Industry 4.0 problems and the reasons for using blockchain-based solutions: WHY?

There are various reasons for applying blockchain to address Industry 4.0 issues, but it is a widely held view in the above literature that from a technical perspective blockchain-based systems are more secure compared to their counterparts (Sahal et al., 2021). This may be explained by several reasons. First, blockchain-based systems are decentralized, thus protecting them from issues related to bottlenecks and single point of failure, which often occur in centralized systems (Gupta et al., 2020; Niya et al., 2020; Abbas et al., 2021; Chauhan et al., 2021). Second, blockchain decentralization often results in distributed systems, thus resolving problems related to centralized control of data, which often results in data breaches (Fernandez-Carames and Fraga-Lamas, 2019). Third, blockchain-based systems are free of trusted third parties, thus not requiring the presence of intermediaries (Adhikari and Winslett, 2019; Aghamohammadzadeh and

Valilai, 2020; Kaynak et al., 2020; Zhu et al., 2020; Vatankhah Barenji, 2021). Moreover, from a management perspective, blockchain introduces decentralized platforms that replace centralized platforms, which rely on the presence of intermediaries and imply high intermediary costs, thus resulting in sustainable business models, where there is no disparity between business partners (Wang et al., 2020; Soni et al., 2021). Furthermore, the transparency of blockchain technology significantly increases the visibility of information and material flows along supply chains (Mukherjee et al., 2020), thus enhancing the monitoring of carbon emissions and the sustainability of manufacturing processes (Khaqqi et al., 2018).

Centralized systems often result in information asymmetry issues among collaborating partners (Ada et al., 2021; Pérez et al., 2022). For instance, production control processes are often governed by few managers, therefore lacking useful information that may be brought up by department managers or even individual workers (Laabs and Dukanović, 2021). One explanation might be that there is a need for a trustful communication platform to share insights between collaborating partners (Fraga-Lamas and Fernández-Caramés, 2019; Wang et al., 2021). Blockchain-based systems show great potential for sharing confidential data without needing to disclose such data (Bamakan et al., 2021; Nasu et al., 2021). The need of trustful platforms in the context of Industry 4.0 often comes from frequent frauds and tampered certifications (Longo et al., 2019; Maryniak et al., 2021). In this regard, Zhang et al. (2022) develop a game theory model based on blockchain technology in the context of shared manufacturing, where the use of blockchain empowers trust between collaborators, which do not necessarily need to know each other. Moreover, the lack of trustful platforms in Industry 4.0 settings often results in the waste of resources, such as long processing delays, elevated energy consumption and costs (Viriyasitavat et al., 2019; Chang, 2020; Viriyasitavat, 2020; Rahman et al., 2021; Viriyasitavat et al., 2022). The immutability of Dapps could resolve the longstanding problem of data tampering in Industry 4.0 settings (Frey et al., 2019; Torrecilla-García et al., 2020; Datta and Bhattacharjee, 2021). Furthermore, blockchain increased interoperability assists on reducing data fragmentation across various business partners (Aguilar-Ramirez et al., 2022).

Most of the current maintenance operations are paper based, thus hindering the accountability of such operations, as well as sometimes rendering untraceable the monitoring of maintenance operations, due to data loss or damage (Stodt et al., 2019; Welte et al., 2020; Aheleroff et al. 2021). Industry 4.0 systems need the controlled access of data to guarantee resilient and reliable systems. However, there are various security and privacy issues in digital manufacturing systems, which are not only caused by external attackers, rather by employees and contractors trying to steal intellectual property (Sturm et al., 2017; Putz et al., 2021). Rodríguez-Espíndola et al. (2022) suggest that the accelerated adoption of blockchain may be due to the enhanced organizational resilience in blockchain-based systems.

4.2 Blockchain and the enabling technologies for resolving industry 4.0 issues: HOW?

As mentioned above, the extant literature combines blockchain technology with the ten main technologies identified by the extant literature (Aledhari et al., 2020; Barata et al. 2020; Bhattacharjee el al., 2020; Hossain et al., 2020; Kumar et al., 2020; Nasu et al., 2021; Puri et al, 2020; Suvarna et al., 2021; Zhu et al., 2020) to resolve industry 4.0 problems. This section will further explain the ten technologies.

First, fog computing, which is also known as edge computing, significantly reduces computation times of big data, by enabling edge devices such as sensors, where data is generated, to process most of produced data. As a result, edge computing provides low computation times for low-latency applications since data computation is mostly done *in loco* (Petrali et al., 2018; Seitz et al., 2018; Lallas et al., 2019; Sittón-Candanedo, 2020; Kumar et al., 2020). Second, AI, deep learning, and federated learning mechanisms, where in federated learning algorithms the training data of machine learning models is not uploaded in a single server, rather machine learning models are trained on various decentralized local samples distributed across various machines. In other words, federated learning algorithms get trained across multiple devices with decentralized data samples without having to exchange the actual data (Aledhari et al., 2020; Arachchige et al., 2020; Khan et al., 2020; Demertzis et al., 2021; Otoum el al.; 2022). Third, smart grids and smart meters, which are frequently mentioned in the energy sector. Smart grids are electrical power delivery networks with information technology capabilities, which can be considered as autonomous electrical distribution systems capable of self-healing, resilient to attacks, and able to forecast future uncertainties (Alcaraz et al., 2020; Hossain et al., 2020; Li et al., 2020a; Li et al., 2020b;; Borowski, 2021; Guan et al., 2021; Kumari et al., 2021; Son et al., 2021; Judge et al., 2022). Fourth, cloud manufacturing, which delivers on-demand manufacturing services, by sharing manufacturing resources and capabilities with external entities, and thus applying sharing economy principles in manufacturing settings (Li et al., 2018; Adhikari and Winslett, 2019; Lillas et al., 2019; Aghamohammadzadeh and Valilai, 2020; Kaynak et al., 2020; Zhu et al., 2020; Rožman et al., 2021; Vatankhah Barenji, 2021). Fifth, multi-agent systems, which are intelligent systems capable of solving complex problems by using sensors and reinforcement learning algorithms (Pinheiro et al., 2019). Sixth, the concept of digital twins, which refers to the digital entity or token of physical assets or processes. A digital twin is the virtual representation of real-world objects or processes (Lin et al., 2018; Barata et al. 2020; Guo et al., 2020; Hasan et al., 2020; Deebak and AL-Turjman, 2021; Sahal et al., 2021; Softic et al., 2021; Putz et al., 2021; Zuo, 2021; Costa et al., 2022; Mazzei et al., 2022). Seventh, industrial internet of things (IIOT) and wearable devices, which refer to systems consisting of interconnected sensors and devices, and exploiting such interconnectedness to yield significant improvements in productivity, efficiency, and a high degree of automation (Seitz et al., 2018; Torrecilla-García et al., 2020; Puri et al, 2020; Kim et al., 2021; Rathee et al., 2021; Chen et al., 2022b). Eighth, encryption techniques, which notably enhance the security features of blockchain-based systems (Nasu et al., 2021). Nineth, clustering algorithms, which are unsupervised learning algorithms that group similar objects (Raschka and Mirjalili, 2019; Bhattacharjee el al., 2020). Tenth, cyber physical systems, which can be seen as platforms that enable communication, computation, and control of an automated manufacturing environment but also synchronize machines with their respective manufacturing facilities (Lee et al., 2019; Yu et al., 2020; Suvarna et al., 2021).

The ten technologies address decentralized systems that involve various end nodes in different industries. For this reason, blockchain technology is used to secure such decentralized systems from many risks, such as the risk of data loss, data tampering, and unauthorized access. Such technologies can be therefore seen as enablers of blockchain use.

4.3 The features of blockchain-based solutions in Industry 4.0 settings: WHAT?

Blockchain technology eliminates high waiting times and delays, thus implementing resilient systems that overcome problems related to single point of failure and bottlenecks (Adhikari and Winslett, 2019; Tang and Veelenturf, 2019; Aghamohammadzadeh and Valilai, 2020;; Kaynak et al., 2020; Zhu et al., 2020; Guan et al., 2021; Long et al., 2021; Vatankhah Barenji, 2021; Lin et al., 2022; Otoum el al., 2022). Moreover, the immutability of data in blockchain-based systems dramatically simplifies the auditability of blockchain data, which implies that blockchain data may be easily used in legal cases without the need of further data elaborations (Mohamed and Al-Jaroodi, 2019; Miehle et al., 2019; Wang et al., 2020; Soni et al., 2021; Lin et al., 2022; Rastogi et al., 2022). In the same vein, blockchain-based solutions enforce the accountability of actions, since all data are recorded in an immutable data structure (Seitz et al., 2018; Shinde et al., 2020; Long et al., 2021; Paul et al., 2021; Lin et al., 2022). For instance, blockchain considerably improves maintenance operations, by recording all maintenance interventions on an immutable record, thus dramatically boosting the accountability of actions during maintenance operations (Stodt et al., 2019; Demertzis et al., 2020; Welte et al., 2020; Aheleroff et al. 2021; Dreyer et al., 2021).

Blockchain considerably increases access to information, thus mitigating, or even eliminating, issues related to information asymmetry (Ada et al., 2021; Duran et al., 2021; Long et al., 2021; Lin et al., 2022; Pérez et al., 2022; Safraz et al., 2022). In the same vein, blockchain significantly improves visibility between global business partners, thus easing verification processes and avoiding missing information interchanges (Casino et al., 2019; Longo et al., 2019; Abreu et al., 2021; Ali et al., 2021; Faridi et al., 2021; Laabs and Dukanović, 2021; Liu et al., 2021; Maryniak et al., 2021; Srivastava et al., 2022). Furthermore, blockchain significantly enhances data interoperability, sharing and distributed storage among globalized business partners (Yan et al., 2017; Frey et al., 2019; Lee et al., 2019; Tang and Veelenturf, 2019; Jo and Park, 2020; Liu el al., 2020; Hassan et al., 2021; Nasu et al., 2021; Sittón-Candanedo, 2020; Suvarna et al., 2021; Teisserenc and Sepasgozar, 2021a; Kumar et al., 2022; Otoum el al., 2022).

A broadly accepted view is that blockchain increases trust between various business actors (Kapitonov et al., 2018; Gupta et al., 2020; Hennebert and Barrois, 2020; Liu el al., 2020; Niya et al., 2020; Abbas et al., 2021; Chauhan et al., 2021; Maryniak et al., 2021; Le et al., 2022). In other words, the blockchain technology efficiently automatizes agreements between autonomous entities (Kumar et al., 2020; Lezoche et al., 2020). As a result, blockchains helps reduce frauds and data tampering, as well as provides a trustful platform for communications in collaborative environments (Fernández-Caramés et al., 2019; Longo et al., 2019; Hopkins and Córdoba, 2021; Khanfar et al., 2021; Sunmola, 2021; Sunmola et al., 2021). Moreover, blockchain empowers efficient certification mechanisms, which are tamper-proof and easily transferable between various entities without hindering their authenticity (Lahbib et al., 2019; Hernandez-de-Menendez et al., 2020; Pannen, 2021; Softic et al., 2021; Costa et al., 2022). Blockchains also enable reputation systems to become transparent and immutable, therefore boosting the value of communications among all stakeholders (Yan et al., 2017; Khaqqi et al., 2018; Jo and Park, 2020; Aoun et al., 2021; Hassan et al., 2021; Leng et al., 2021).

Blockchain technology can enforce privacy and information secrecy when combined with other technologies (Lin et al., 2018; Arachchige et al., 2020; Sittón-Candanedo, 2020; Deebak and AL-Turjman, 2021; Demertzis et al., 2021; Rathee et al., 2021; Soni et al., 2021). For instance, blockchain-based systems, coupled with with encryption techniques, can exchange confidential data between various actors without the need of disclosing data, thus implementing secure, reliable and resilient systems (Lee et al., 2019; Miehle et al., 2019; Chang, 2020; Sodhro et al., 2020; Ho et al., 2021; Kim et al.,2021; Putz et al., 2021; Softic et al., 2021; Stepanov, 2021; Suvarna et al., 2021; Teng et al., 2021; Aguilar-Ramirez et al., 2022; Hameed et al., 2022; Viriyasitavat et al., 2022). Moreover, findings in the literature are widely interpreted as providing support for the improved (real-time) traceability of blockchain-based solutions (Seitz et al., 2018; Ivanov et al., 2019; Mohamed and Al-Jaroodi, 2019; Bodkhe et al., 2020; Helo and Shamsuzzoha, 2020; Mehta et al., 2020; Welte et al., 2020; Abbas et al., 2021; Abreu et al., 2021; Faridi et al., 2021; Ho et al., 2021; Hong et al., 2021; Rodrigues et al., 2021; Huo et al., 2022; Kayikci et al., 2022; Raimundo and Rosário, 2022). Furthermore, blockchain hybrid systems show promising potential for implementing scalable data processing systems, which offer fine-grained access control (Petrali et al., 2018; Lin et al., 2018; Chang, 2020; Sittón-Candanedo, 2020; Rahman et al., 2021; Putz et al., 2021; Viriyasitavat et al., 2022).

Finally, blockchain considerably improves the sustainability of processes by providing a reliable platform that can easily identify wastes, as well as implements credible sustainability certification to document and verify sustainable practices from the source until the destination (Mukherjee et al., 2020; Asante et al., 2021; Balasubramanian et al., 2021; Khanfar et al., 2021; Sunmola, 2021; Teisserenc and Sepasgozar, 2021a). For instance, blockchain could help dramatically reduce carbon emissions (Fu et al., 2018; Khaqqi et al., 2018). Furthermore, blockchain when combined with other technologies is likely to result in cost and power efficient systems (Kimani et al., 2020; Sodhro et al., 2020; Sunny el al., 2020; Kim et al., 2021; Srivastava et al., 2022).

5 Conclusion and future research directions

This research aims to summarize the major applications of blockchain technology in Industry 4.0 settings, highlighting why blockchain technology is used in Industry 4.0 applications, how industry 4.0 problems are resolved (or at least mitigated) by using blockchain technology, and what the main features of blockchain-based solutions are.

This study offers a number of findings that have remarkable implications for the current literature focusing on the use of blockchain technology in Industry 4.0 settings. First, the most obvious finding to emerge from this study is that blockchain is still at its introduction stage in the technology life cycle. In fact, many solutions were proposed in the academic literature. However, the application of blockchain-based solutions on industrial level is still limited. This may be due to blockchain security issues (Leng et al., 2022c). Moreover, the blockchain technology is still at its introduction stage in the technology life cycle and as such is rapidly evolving over time. This implies that new academic contributions constantly emerge, thus making literature reviews quickly outdated. To overcome this limitation, we enhance the value of our work adding two more contributions for the research on the use of blockchain technology in Industry 4.0 settings from a manufacturing and operations management perspective. Indeed, we first propose a framework (built upon the extant literature), which not only gives a general overview of the main applications of blockchain technology in the context of Industry 4.0, but also clearly identifies why and how blockchain technology is used in this context and which features blockchain technology solutions displays for resolving the emerging issues. Second, we identify several open questions for future research, which remain unanswered at present and thus need the involvement of information technology, manufacturing, and operations management scholars and practitioners for a comprehensive understanding of the implied technological and managerial challenges and the possible paths for resolution. These questions are fully reported in Table 1 and discussed in what follows.

Our study explains that there are ten main technologies that are frequently combined with blockchain technology to resolve Industry 4.0 issues. For instance, both Petrali et al. (2018) and Sittón-Candanedo (2020) suggest combining edge computing with blockchain, whereas both Arachchige et al. (2020) and Demertzis et al. (2021) suggest combining federated learning techniques with blockchain technology. However, as of now, a more detailed study investigating why and when each specific technology among the enabling ones should be used in Industry 4.0 settings is still missing. In other words, what is the added value by each enabling technology when it is combined with blockchain technology?

Blockchain technology is showing great potential for implementing Industry 4.0 systems (Adhikari and Winslett, 2019; Fernandez-Carames and Fraga-Lamas, 2019). In this regard, some scholars suggest that blockchain-based cloud manufacturing systems might soon replace traditional systems (Aghamohammadzadeh and Valilai, 2020; Kaynak et al., 2020; Zhu et al., 2020; Vatankhah Barenji, 2021). However, more research needs to be conducted to determine whether blockchain-based systems would substitute current systems or complement them. Moreover, current software systems are often implemented in a centralized manner, thus impeding information sharing and increasing data fragmentation between collaborating business actors (Aguilar-Ramirez et al., 2022). Blockchain technology could be used to address such issue, by connecting all business partners in a decentralized manner, thus resulting in a collaborative environment (Belhi et al., 2020; Liu el al., 2020; Stepanov, 2021). For these reasons, it would be interesting to assess the effects of blockchain technology on software vendors, and specifically on whether the adoption of blockchain-based systems results in higher in-house software development activities rather than outsourcing such activities to software vendors.

Even though blockchain immutability and traceability allows adherence to human rights, such as fair and safe working conditions, since recorded data cannot be later modified (Eashwar and Chawla, 2021; Hong et al., 2021; Razak et al., 2021; Huo et al., 2022), the adoption of blockchain-based systems is still at a very early stage. Exploring the reasons of such delayed adoption is intriguing. Some authors suggest that the lack of regulations for blockchain technology is one of the reasons behind the late adoption of blockchain technology in Industry 4.0 contexts (Al Barghuthi et al., 2019; Etemadi et al., 2021; Vu et al., 2021). In the same vein, as suggested by several scholars (e.g., Leng et al., 2022a; Leng et al., 2022c), the blockchain itself also has security issues, which poses some challenges for future developments. According to Leng et al. (2022c), these issues can be categorized into three main levels: process (referring to smart contracts, implementation security, operation standards, and fraud detection), data (consisting of authentication, encryption, consensus algorithms, access control, and key management), and infrastructure (encompassing terminal devices, network, and super-node server) levels. While different technologies have been proposed into the blockchain to enhance the security, transparency, traceability, as well as regulatory aspects, more research is required on this matter.

A broadly accepted view in the above literature is that blockchain dramatically increases the transparency of information in manufacturing and supply chain settings (Longo et al., 2019; Gong et al., 2020; Grecuccio et al., 2020; Benzidia et al., 2021; Rodrigues et al., 2021; Wamba and Queiroz, 2022). These findings provide insights for future research to investigate whether and how policy makers would mandate blockchain-based systems for a better monitoring of markets. Moreover, the increased transparency of blockchain technology could fill the gap of missing communications among policy makers, manufacturers, and the general public (Kapitonov et al., 2018; Gupta et al., 2020; Niya et al., 2020; Abbas et al., 2021; Chauhan et al., 2021; Majeed et al., 2021). In the same vein, given the increased transparency of NFT property certificates, future research could therefore investigate the adoption of NFTs from both policy makers' and manufacturers' sides (Carayannis et al., 2022). More broadly, research is also needed to determine whether companies are also adopting NFTs to document their business and manufacturing assets, but the relative adoption stage of NFTs (Lin et al., 2022; Rastogi et al., 2022).

We have observed broad agreement in the literature that blockchains significantly reduces information asymmetry (Fraga-Lamas and Fernández-Caramés, 2019; Ada et al., 2021; Wang et al., 2021; Pérez et al., 2022). In this regard, blockchain technology could remove barriers of entry in various markets, therefore enabling small and medium enterprises to compete with well-established competitors. Further research regarding the role of blockchain technology would be of great help in determining whether and how market concentration would be affected by such technology.

Even though some blockchains have high energy consumptions, some scholars suggest that blockchain technology has far more potential to bring sustainability in supply chains than traditional supply chains due to increased automation, visibility, and integration (Mukherjee et al., 2020; Asante et al., 2021; Khan el al., 2021). More research is required on the environmental impact of blockchain technology. For instance, it would be interesting to investigate whether final consumers appreciate blockchain-based energy certifications (Teng et al., 2021). In general, research is also needed to determine the sustainability impact of blockchain adoption on the relationship between all stakeholders, since most of the current studies are focused on final customer relationships (Lezoche et al., 2020; Stanisławski and Szymonik, 2021).

Blockchain technology is showing great potential for developing accurate tracking systems capable of offering real-time traceability of products, thus ensuring consumption safety (Ivanov et al., 2019; Casino et al., 2020; Galanakis et al., 2021; Kayikci et al., 2022). Moreover, the use of blockchain technology allows firms to promote their core values, such as sustainable materials, recycled plastic use, and authentic materials along the supply chain. In other words, products can be easily verified by using a Dapp (Ali et al., 2021), thus positively impacting manufacturer-customer relationships (Stanisławski and Szymonik, 2021). However, there are few real-life applications that use blockchain technology for tracking consumer products. It is desirable that future studies identify the reasons behind such gap of applications, but also what can be done to further accelerate the introduction of blockchain technology for tracing consumer products.

More information on the effect of the crypto market on the adoption of blockchain technology would help to establish a greater degree of accuracy on this matter.

Finally, blockchain technology significantly improves the transparency of maintenance operations since all stakeholders are able to visualize performed maintenance operations and, at the same time, are forced to correctly perform maintenance operations due to the fact that all maintenance operations are recorded on the blockchain (Stodt et al., 2019; Welte et al., 2020; Aheleroff et al. 2021). Nevertheless, empirical evidence based on large surveys that demonstrates the advantages of blockchain adoption for maintenance operations is still missing and is definitely worth future research.

Table 1 - Future research directions

Research gap	Research stream	Related literature
Will blockchain technology replace existing centralized infrastructures or complement them in future Industry 4.0 settings?	The future of blockchain use	Adhikari and Winslett, 2019; Fernandez-Carames and Fraga-Lamas, 2019; Aghamohammadzadeh and Valilai, 2020; Kaynak et al., 2020; Zhu et al., 2020; Vatankhah Barenji, 2021
Will blockchain incentivize companies to implement their own systems in-house, rather than using systems produced by software vendors?	The impact of blockchain on software vendors	Belhi et al., 2020; Liu el al., 2020; Stepanov, 2021; Aguilar-Ramirez et al., 2022
Under which conditions and with which modalities will policy makers incentivize the use of NFTs for legal certifications?	NFTs and policy makers	Carayannis et al., 2022; Rastogi et al., 2022; Lin et al., 2022
Are firms adopting NFTs for certifying their business/manufacturing assets? Which adoption stage are we currently at?	The adoption of NFTs on the business and/or manufacturing level	Carayannis et al., 2022; Rastogi et al., 2022; Lin et al., 2022
Given the improved transparency of blockchain technology, how will policy makers require all businesses to adopt blockchain technology for a better monitoring of markets in Industry 4.0 settings?	Blockchain transparency and market monitoring	Fernández-Caramés et al., 2019; Iswari et al., 2019; Longo et al., 2019; Barata et al., 2020; Bodkhe et al., 2020; Gong et al., 2020; Grecuccio et al., 2020; Kurnia et al., 2020;; Muzylyov and Shramenko, 2020; Popkova and Sergi, 2020; Wang et al., 2020; Živić, 2020; Ada et al., 2021; Bedi et al., 2021; Benzidia et al., 2021; Dietrich et al., 2021; Maryniak et al., 2021; Menon and Jain, 2021; Reno et al., 2021; Rodrigues et al., 2021; Chen et al., 2022a; Chen et al., 2022b; Raimundo and Rosário, 2022; Wamba and Queiroz, 2022
Will blockchain technology and its application to Industry 4.0 remove barriers of market entry for small and medium enterprises (SMEs).	The effect of blockchain technology on competitiveness of SMEs and market concentration	Fraga-Lamas and Fernández-Caramés, 2019 ; Wang et al., 2020; Ada et al., 2021; Soni et al., 2021; Pérez et al., 2022; Wang et al., 2021

What will be the environmental impact of blockchain technology on the evolution of supply chains?	The green impact of blockchain technology on supply chains	Fu et al., 2018; Esmaeilian et al., 2020; Glavanits, 2020; Mukherjee et al., 2020; Asante et al., 2021; Khan el al., 2021; Khanfar et al., 2021; Sunmola, 2021; Sunmola et al., 2021
What are the reasons behind the few blockchain-based applications for ensuring product safety? What can be done to accelerate blockchain use in product safety regulations?	Product safety and blockchain technology	Ivanov et al., 2019; Casino et al., 2020; Kouhizadeh et al., 2020; Galanakis et al., 2021; Kayikci et al., 2022
What is the perception of blockchain-based systems among all stakeholders in Industry 4.0 settings? Are there any conflicting views among them?	Industry 4.0 stakeholders' perception of blockchain-based systems	Lezoche et al., 2020; Stanisławski and Szymonik, 2021
Why and when to combine blockchain technology with certain technologies such as the ten enabling technologies? What is the added value by each technology when it is combined with blockchain technology?	Blockchain technology and digital manufacturing	Petrali et al., 2018; Lee et al., 2019; Arachchige et al., 2020; Bhattacharjee el al., 2020; Kumar et al., 2020; Sittón-Candanedo, 2020; Sodhro et al., 2020; Sunny el al., 2020; Demertzis et al., 2021; Kim et al., 2021; Suvarna et al., 2021
Blockchain transparency and improved communications positively affect the relationships with final consumers. However, do transparency and improved communication enabled by blockchain technology positively affect all stakeholders? Are there differences between suppliers and customers in this regard?	The impact of blockchain technology on relationships between stakeholders	Stanisławski and Szymonik, 2021; Stepanov, 2021; Aguilar-Ramirez et al., 2022
Does blockchain technology increase the accountability of actions during maintenance operations?	Maintenance operations and blockchain technology	Stodt et al., 2019; Welte et al., 2020; Aheleroff et al. 2021; Dreyer et al., 2021
Do final consumers appreciate blockchain-based renewable energy certifications?	Blockchain-based renewable energy certifications and consumer perception	Teng et al., 2021
Although it can significantly improve the monitoring of workers' vital health data, why do we still observe few applications of blockchain technology for health safety in manufacturing jobs?	The safety of workers in manufacturing	Torrecilla-García et al., 2020; Eashwar and Chawla, 2021; Hong et al., 2021; Rathee et al., 2021; Razak et al., 2021; Huo et al., 2022
Is the lack of blockchain applications in Industry 4.0 settings related to the lack of national government interventions, thus the deficiency of regulations regarding the use of blockchain technology, as well as the existence of security issues?	Blockchain technology regulations for Industry 4.0 and security issues	Al Barghuthi et al., 2019 Etemadi et al., 2021 ; Vu et al., 2021; Leng et al., 2022a; Leng et al., 2022c

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