

Review article

Blockchain application to the processes in material design, production, distribution, and disposal: A survey

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ABSTRACT

Data is a valuable resource that can facilitate the development of advanced products sustainably and transparently. However, issues like data manipulation, forgery, and deletion can damage data reliability, limiting its use during product development. In this paper, we aim to identify and explore solutions that relieve data reliability concerns throughout the life of a product. Specifically, we investigate the implementation of blockchain to mitigate data-related problems that affect product development. Blockchain is a decentralized and immutable ledger where information is inherently protected against tampering. To understand how product development can benefit from blockchain, we first identify data-dependent processes across four stages of the product's life (i.e., design, production, distribution, and disposal) and present the challenges these processes face. We then discuss blockchain-based techniques to tackle these challenges. Finally, we outline the benefits of utilizing blockchain across the four stated stages of the product's life. Previous surveys in this area are limited to discussing the application of blockchain to a subset of these four stages. Additionally, previous surveys do not consider the use of blockchain in materials design. In contrast, we provide a comprehensive survey that examines the utility of blockchain during the design, production, distribution, and disposal of products. Further, our survey presents how blockchain can be implemented to aid materials design. This survey provides researchers and practitioners insights into how blockchain can be applied to enhance different aspects of product design, production, distribution, and disposal.

1. Introduction

In recent years, there has been a growing demand for increased sustainability and transparency in product development, driven by evolving consumer expectations. Addressing this demand requires ensuring data reliability, which is an important task throughout product development, as data powers the tools needed to develop products sustainably and transparently. However, data reliability is threatened by issues such as manipulation, forgery, and deletion, which limits its value throughout product development. To explore solutions that enhance data reliability throughout the life of a product, we divide the life of a product into four stages, i.e., design, production, distribution, and disposal stages. Generally, in the design stage, researchers design materials to create useful products. In the production stage, manufacturing facilities enable the mass production of these products. In the distribution stage, supply chain entities make sure to quickly deliver the products to their users. Finally, in the disposal stage, recycling facilities recover as much material as possible to minimize waste.

The four stages benefit from the implementation of emerging technologies such as artificial intelligence (AI), additive manufacturing

(AM), and Internet-of-Things (IoT). Although these technologies are beneficial for the sustainable and transparent development of products, they introduce new obstacles that need to be addressed. For instance, the use of AM in the production stage requires factories to protect against cyber attacks targeted at AM devices. If the attacks are left unattended, malicious parties could damage products and create counterfeits [1]. Similarly, IoT devices used in supply chains to collect product data at the distribution stage could be compromised and cloned onto counterfeit products, damaging the reliability of supply chains [2]. It is useful to develop solutions that allow for the use of these technologies with less concern.

A promising technology that can address the challenges in the four stages is blockchain. In short, a blockchain is a decentralized and immutable ledger of information. Although blockchain has been primarily applied in financial applications, it can be extended to many industries such as engineering [3] or healthcare [4]. By utilizing blockchain, industries can protect information against tampering and a single point of failure. The design, production, distribution, and disposal of products can also benefit from blockchain technology. For instance,

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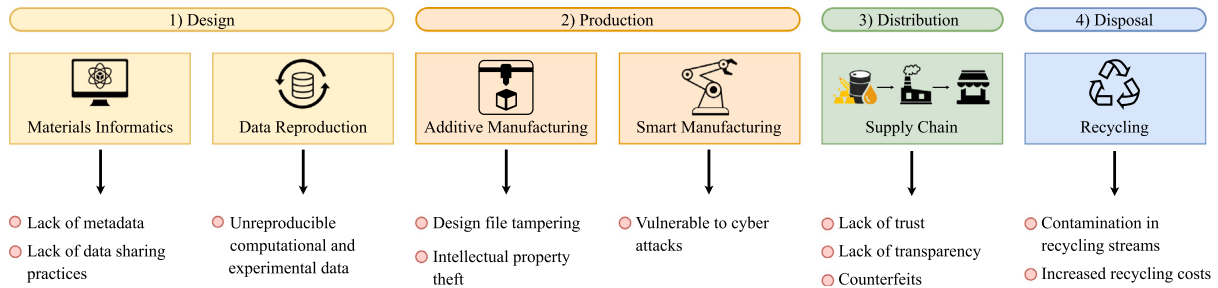


Fig. 1. Technologies and processes with their respective challenges that are present in the design, production, distribution, and disposal of a product.

manufacturing factories in the production stage can store manufacturing data, like computer-aided design (CAD) files, in a blockchain to prevent tampering [5]. Similarly, supply chains in the distribution stage can store product data gathered by sensors in a blockchain to make it immutable and accessible to the participants of the supply chain [6].

To understand how blockchain can be implemented, this paper provides a comprehensive survey that explores the influence of blockchain in the design, production, distribution, and disposal of products. Specifically, this survey will examine the challenges each stage faces, highlight blockchain-based solutions to address these issues, and demonstrate the benefits of using blockchain. Previous studies usually discuss the use of blockchain to a subset of these stages [3,7–11]. In contrast, our review discusses these four stages in unison to present a thorough overview of blockchain's capabilities to support product development. Additionally, we expose readers to multiple blockchain-based techniques designed to solve challenges at each stage. Further, this survey includes the application of blockchain to materials design, which is an important aspect of product development. To the best of our knowledge, this is the first survey paper that includes the application of blockchain to materials design. Our paper explores blockchain's applicability in materials design to further introduce blockchain to materials science and provide insights to researchers working in this domain.

Our work will highlight several technologies and processes in the design, production, distribution, and disposal of products. Specifically, this work focuses on materials informatics, data reproducibility, AM, smart manufacturing, supply chain management, and recycling. These processes and technologies are crucial to a stage of the product's life but these six topics face individual challenges that burden their proper application (see Fig. 1). In this paper, the application of blockchain to resolve the challenges within the six identified topics will be explored. By examining the blockchain applications, it is possible to identify the specific aspects blockchain can be used to contribute in the design, production, distribution, and disposal of products.

1.1. Methodology

In order to understand how blockchain can support the design, production, distribution, and disposal of products, this paper seeks to explore existing literature on the application of blockchain to material informatics, data reproducibility, AM, smart manufacturing, supply chain management, and recycling. We first conducted an initial literature search using multiple databases and specific keywords to find relevant literature on these topics. Then, we filtered the starting body of literature using defined inclusion and exclusion criteria.

Initial literature search: For each of the topics in question, we conducted separate literature searches. The search was carried out utilizing databases such as Scopus, Google Scholar, and IEEE Xplore. Further, we utilized the keywords outlined in Table 1 within the specified databases to find the targeted literature. As a result, we gathered 943 studies over all the topics.

Selection criteria: We utilized specific inclusion and exclusion criteria to dismiss papers that were not relevant to our study. The inclusion criteria were: (a) papers that include frameworks or applications of

blockchain to the processes and technologies that will be discussed in this study. These studies will demonstrate exactly how blockchain can be applied in the areas this paper surveys; (b) studies that review or survey the application of blockchain to the areas in question. Exploring these papers will reveal clear challenges that burden these areas and the benefits from implementing blockchain. The exclusion criteria were papers that did not have relevant information about material informatics, data reproducibility, AM, smart manufacturing, supply chain management, or recycling.

Following this selection process, we obtained a total of 85 studies. The articles collected will be used to determine the challenges, blockchain-based solutions, and benefits of utilizing blockchain in the topics at hand. Additionally, we included 29 papers that review the 6 topics individually without the influence of blockchain to further understand these topics and their challenges. Overall, the work discusses 114 articles.

1.2. Literature review

Previous studies have focused on the use of blockchain to boost manufacturing facilities, supply chain processes, and waste management systems. For instance, there are works that explore how blockchain can facilitate automation in semiconductor foundries [12, 13] and data sharing between sheet metal suppliers and forming companies [14]. Additionally, studies have discussed the use of blockchain to improve transparency and traceability within the supply chain of electronic materials [15,16], ceramic products [17], precious metals [18], and composite materials [19]. Similarly, the use of blockchain to reduce electronic [20,21], ceramic [22], and polymer waste [23–30] has been considered.

Rather than focusing on a singular material and system, this study focuses on the application of blockchain to the processes that are present during the design, production, distribution, and disposal of products. In literature, the use of blockchain for production, distribution, and disposal operations has been introduced. However, the use of blockchain to assist in the design of materials has not been widely examined. In the production space, blockchain has been applied to improve manufacturing systems by securing CAD files used in AM [5, 31–34] and by enabling advanced manufacturing schemes like smart manufacturing [10,35–39]. In the distribution space, studies have utilized blockchain to protect supply chains against counterfeiting [2,40], to increase collaboration between untrusted supply chain parties [41], and to facilitate data transparency and traceability within a supply chain [6,8,42–46]. Finally, in the disposal space, blockchain has been proposed to enable the traceability of waste so that stakeholders can ensure solid waste reaches the correct processing plant [11,47–51]. Moreover, blockchain has been used to encourage proper recycling practices [28,30,52–54] and to ensure recyclable materials get recycled [9,21,55]. In general, these works highlight how blockchain helps solve cybersecurity issues like data tampering and intellectual property (IP) theft. These papers also presented blockchain's capability to increase communication and transparency between untrusted entities.

Table 1

Literature search performed with Scopus, Google Scholar, and IEEE Xplore for blockchain applications to materials informatics, data reproducibility, AM, smart manufacturing, supply chains, and recycling.

Subject	Keywords	Initial literature	Final literature
Material informatics	“Blockchain” AND “Materials informatics”	59	2
Data reproducibility	“Blockchain” AND “Reproducibility”	173	4
AM	“Blockchain” AND “Additive manufacturing”	154	14
Smart manufacturing	“Blockchain” AND “Smart manufacturing”	198	25
Supply chains	“Blockchain” AND “Supply chain”	230	19
Recycling	“Blockchain” AND “Recycling”	129	21

Table 2

A comparison between our survey and other works.

References	Year	Description
[10]	2020	Surveyed the application of blockchain in sustainable manufacturing and product lifecycles.
[3]	2020	Discussed and categorized blockchain applications in general manufacturing and engineering.
[11]	2021	Proposed a blockchain solution for supply chain and waste management of COVID-19 medical equipment.
This work	2023	Explored the application of blockchain to material design, highlighted the challenges in related fields, and outlined blockchain-based solutions for material design, production, distribution, and disposal.

To the best of our knowledge, there is little research work that discusses the application of blockchain to materials design [56,57]. Similar to production, distribution, and disposal, materials design involves the collaboration between multiple parties and the mass collection of data. Blockchain can be useful in this area to resolve trust issues collaborating parties may have and to secure sensitive materials science data against tampering. As such, blockchain can facilitate the use of technologies in materials design that depend on collecting data from multiple sources, e.g. materials informatics. Moreover, it is possible to facilitate the design of new materials by improving the technologies that influence material design through blockchain. This paper will examine how blockchain can be used to facilitate materials design.

Additionally, we conduct a comprehensive survey that not only scopes the application of blockchain to materials design, but also scopes the production, distribution, and disposal of products. As shown in Table 2, there are other works that review multiple stages of product development in unison. Specifically, Leng et al. surveyed the application of blockchain in sustainable manufacturing and Industry 4.0, which included blockchain applications for manufacturing facilities, supply chains, and recycling [10]. Kasten discussed the use of blockchain in general manufacturing and supply chain applications [3]. Ahmad et al. proposed a method that integrated blockchain with both the supply chain and waste management of COVID-19 medical equipment [11]. In our work, we review the four major topics, i.e., design, production, distribution, and disposal, in one paper. Moreover, this work differs from papers that study blockchain applications in supply chain management. Supply chain based papers usually focus on how blockchain can help trace products throughout their life. In contrast, this paper not only discusses how blockchain can improve product traceability, but also how it can promote data sharing in materials science, protect manufacturing systems against cyber attacks, and encourage proper recycling practices. Overall, this paper will highlight the application of blockchain to the design, production, distribution, and disposal of products by outlining the existing challenges, blockchain-based solutions, and prospective benefits. The contributions of this paper are as follows:

- Provided a comprehensive study that discusses the use of blockchain within the design, production, distribution, and disposal of products.
- Identified a research gap in blockchain related literature regarding the implementation of blockchain within materials design.
- Presented challenges and blockchain implementation from the perspective of the industries that work on the design, production, distribution, and disposal of products. Additionally, we outlined the benefits of implementing blockchain in these sectors.

In the following sections, we will introduce blockchain and show use cases of blockchain in the design, production, distribution, and disposal stages of products. Specifically, Section 2 will introduce blockchain and its properties. Section 3 highlights the main topics of the paper. Section 4 and Section 5 will describe the challenges and blockchain implementations in the four stages, respectively. Section 6 discusses the benefits of applying blockchain to the four stages. Fig. 2 shows the structure of this paper.

2. Why Apply Blockchain?

Blockchain is a novel technology that was popularized with the creation of Bitcoin. Bitcoin is a peer-to-peer electronic currency that uses blockchain to validate and store transaction information between multiple users [58]. A blockchain is capable of agreeing on and storing data in a decentralized and immutable fashion. These characteristics allow blockchain to provide a trusted network where multiple users can exchange and store tamper-proof information. This network is suitable in areas like finance [59], government [60], business [61], health-care [4], and engineering [3]. Blockchain has found varied applications because many industries rely on the collection and distribution of data. The widespread use of data gives great value to the trust and data security solutions blockchain can provide.

Blockchain can be beneficial to the industries that manage product design, production, distribution, and disposal. One of the main contributions blockchain provides is the ability to protect a system against dishonest behavior. Dishonest behavior can take many forms such as publishing erroneous or irreproducible data, tampering with design files, creating counterfeits, or lying about waste practices. Preventing this sort of behavior would remove a large burden on these industries. Therefore, it is crucial to develop and utilize solutions, like blockchain, to tackle malicious activity.

Malicious activities occur in the digital realm, where dishonest parties seek to steal or tamper with private or public data. This is problematic since the creation and distribution of data are pervasive throughout the life of a product. Due to the success of data-driven methods and the implementation of novel ideas like Industry 4.0, data is created along the products' life, from its design to its disposal. For example, during the design of a material, data is gathered from simulations or experiments. In the production step, manufacturing facilities rely on digital files containing the design of their products. During distribution, data is collected along every step in a supply chain. Finally, throughout the disposal, data is collected on the waste composition and location. This information is highly important and needs to be protected against unauthorized manipulation. If this challenge is not addressed, it may lead to an increase in counterfeited products, IP theft, or even damage to the manufactured products [1]. To counteract

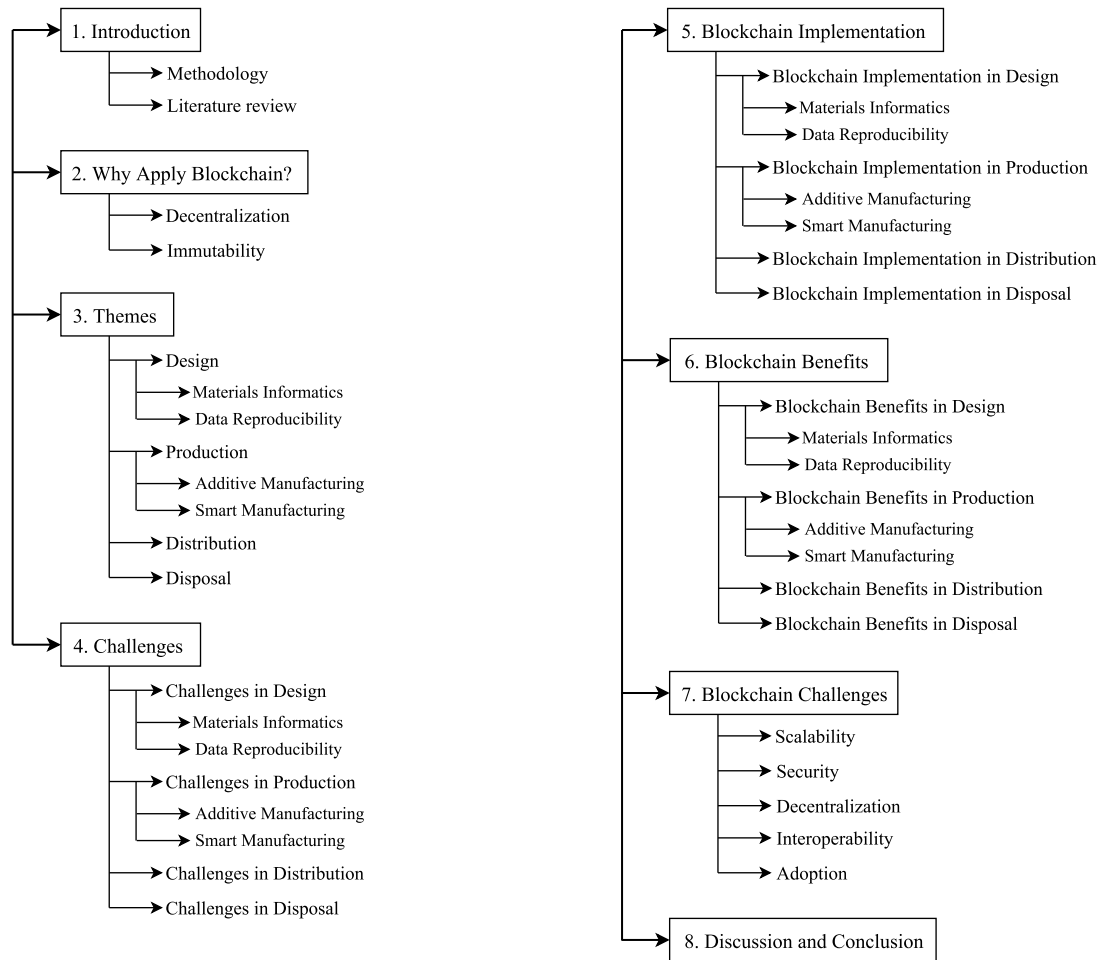


Fig. 2. Illustrative organizational structure.

these issues, blockchain can provide the tools needed for industries to protect their data. Blockchain can protect against malicious activity due to two important properties, decentralization and immutability. These two properties allow blockchain to create an immutable ledger of information that is controlled by all the participants in the network. We will explain how blockchain acquires those two properties below.

2.1. Decentralization

Decentralization is achieved when the control over a certain process is distributed over various parties. In a blockchain, the process that is distributed is the authority over who gets to add new blocks to the chain. A block is a data structure containing information that has been broadcasted by the members of a network. Ideally, no specific entity should have control over the information stored in the blockchain, rather everyone should get the chance to write new information. To this end, blockchain will naturally create a decentralized environment where everyone has their copy of the ledger and the opportunity to add new blocks.

Blockchains implement consensus algorithms to prevent dishonest activity [58,62–71]. A consensus algorithm is essentially a protocol that the nodes in the network will have to follow in order to propose new blocks onto the chain. The protocol is designed such that only correct and truthful information is recorded on the blockchain. As a result, all the nodes in the network will trust the blockchain without necessarily trusting the participants of the network. For participants in the network to propose a block, they have to follow the rules indicated by the

consensus algorithm. Then, the network nodes can safely add that block to their copy of the ledger since they know that the block followed the pre-established protocol. Moreover, by utilizing a protocol that controls how information is added, the blockchain can safely distribute the authority to write information to all the participants in the network, creating a secured decentralized system.

Decentralization is advantageous since it removes the need for third-party organizations to validate, share, or store data. Removing the third party avoids the risk of having a malicious organization taking care of the data and also speeds up processes that were reliant on the third party. Additionally, decentralization further protects the data by removing the single point of failure vulnerability of centralized systems. For example, if information is managed by a central node and the central node fails or is found to be dishonest, the information it managed becomes unusable. In contrast, when the information is managed by the participants of a network that agree on what to store, it is still possible to consider the information reliable if some of the participants fail or are dishonest. An example of a centralized and decentralized system is shown in Fig. 3. Though in the original blockchain, everyone is allowed to participate, new types of blockchains have been created to restrict access from users. These cases are from private and consortium blockchains, where only selected users are able to participate in the blockchain.

2.2. Immutability

Consensus algorithms along with blockchain's special structure allow blockchain systems to achieve immutability. In a blockchain, data

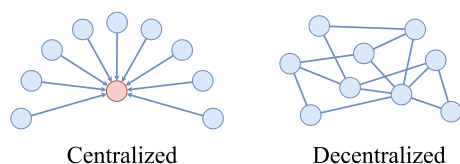


Fig. 3. Centralized vs decentralized system.

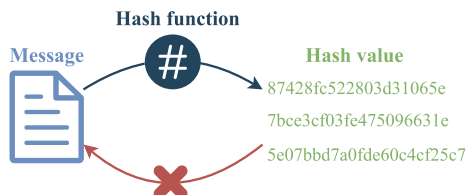


Fig. 4. Hash function example.

is stored in organized blocks that are structured such that they are linked to the blocks behind them. To link the blocks together, the blockchain takes advantage of hash values, which are alphanumeric strings generated through cryptographic functions. These functions, known as hash functions, take a message as an input and output a unique string that cannot be converted back to the original message, as shown in Fig. 4. Additionally, any change to the original message will result in a completely different hash value. Blockchain uses this technique by having each block store the hash value of the block behind it. If any data is altered inside a block, the block's hash value will change and no longer coincide with the hash value stored in the following block. Thus, any tampering would be easily detected.

If a malicious party wanted to conceal the tampering of a block, they would have to remake the following blocks. This means that they would have to follow the consensus algorithm to recreate all of the blocks following the one they tampered with. In Bitcoin for example, recomputing a large number of blocks can be computationally infeasible due to the complexity of its consensus algorithm, known as Proof-of-Work. Furthermore, by using hash values and consensus algorithms, a blockchain can create a ledger of information that is virtually immutable as tampering would be extremely difficult.

In addition to an immutable ledger of information, a blockchain can also store executable code, labeled as a smart contract. Smart contracts were popularized by Ethereum, a leading blockchain system [62]. To execute smart contracts, Ethereum established a virtual machine (called Ethereum virtual machine) powered by the computers that are part of the network. Immutable ledgers in conjunction with smart contracts are the building blocks of various general applications like IP protection, secure information, currency, or products exchanges, reliable tracing, and decentralized software. As shown in Fig. 5, employing these applications to materials informatics, data reproducibility, AM, smart manufacturing, supply chains, and recycling brings about benefits that can reduce the challenges in these areas. Mitigating the issues that burden each topic advances the current technology.

3. Themes

In this section, the four stages, i.e., the design, production, distribution, and disposal, of products will be introduced (see Fig. 6). In addition, we will conduct a keyword co-occurrence analysis on the available literature. The keyword co-occurrence analysis reveals the most common keywords in a body of literature as well as how often these words appear together. By analyzing the co-occurrence of keywords within literature, we can find the common themes that are explored by different studies. We will use the data from Scopus and text visualization software, VOSviewer, to perform the keyword co-occurrence analysis.

3.1. Design

A crucial area in materials science is the design of improved materials to address today's engineering problems. Within materials design, accessible and reliable data is essential as it can enable data-driven methods that can characterize, design, and discover materials [72–76]. Since blockchain can manage and secure different types of data, it can be applied to materials design. This section will discuss two areas within material design that deal with the findability, accessibility, interoperability, and reusability of data. These areas are materials informatics and data reproducibility. Material informatics discusses the use of data-driven approaches to characterize current and novel materials. Data reproducibility focuses on the ability to recreate experimental or computational data to build upon existing work, advancing material science.

3.1.1. Materials informatics

Materials informatics is a field combining materials science and data science that strives to use data-driven techniques to support the design and discovery of novel materials [77,78]. This field introduces a new paradigm that works in conjunction with the three paradigms of materials research, i.e., experimentation, theory, and computation [79, 80]. The idea is to take advantage of previously collected experimental or computational data by using machine/deep learning models to predict the behavior, properties, or composition of current and novel materials [79]. By supporting data-driven techniques with substantial experimental or computational data, it is possible to accelerate the exploration of the vast chemical space for materials, enabling the rapid discovery of materials with improved properties. Without materials informatics, researchers need to rely on traditional material screening methods. However, while traditional methods have been proven useful, they rely heavily on trial and error [72]. Moreover, by using materials informatics, material scientist can not only speed up their research but also reduce the needed resources.

Blockchain and material informatics: Our literature search revealed that there is very little work displaying the application of blockchain to material informatics. After a thorough search through Scopus, Google Scholar, and IEEE Xplore databases using the keyword “blockchain” in conjunction with either “material informatics”, “materials science”, or “materials database” we only found two studies that took advantage of blockchain to create a materials database [56,57]. Within these studies, the main application of blockchain is to secure materials data.

3.1.2. Data reproducibility

The ability to recreate scientific findings and reach similar conclusions as previous studies is an essential aspect of academic research. Such reproducibility can be achieved when research works clearly and openly describe the methodologies used to reach a set of results [81]. Further, being honest about these methods also maintains academic integrity and allows the public to trust scientific discoveries [82]. Additionally, making sure research work is reproducible and trustworthy allows future scientists to effectively build upon existing work [81].

Blockchain and data reproducibility: Like material informatics, there are only a few studies that explore the potential of blockchain to enable the reproducibility of data within materials science or related fields. Searching with Scopus, Google Scholar, and IEEE Xplore, using keywords like “blockchain”, “reproducibility”, and “science” we found four studies relating blockchain and data reproducibility in chemistry [83–85]. In addition to blockchain and reproducibility, these studies look at themes such as the reproducibility of computational data [83,84], molecular dynamics results, or experimental data [85].

3.2. Production

The production stage focuses on the processes used to manufacture material products. After a material with desired properties is designed

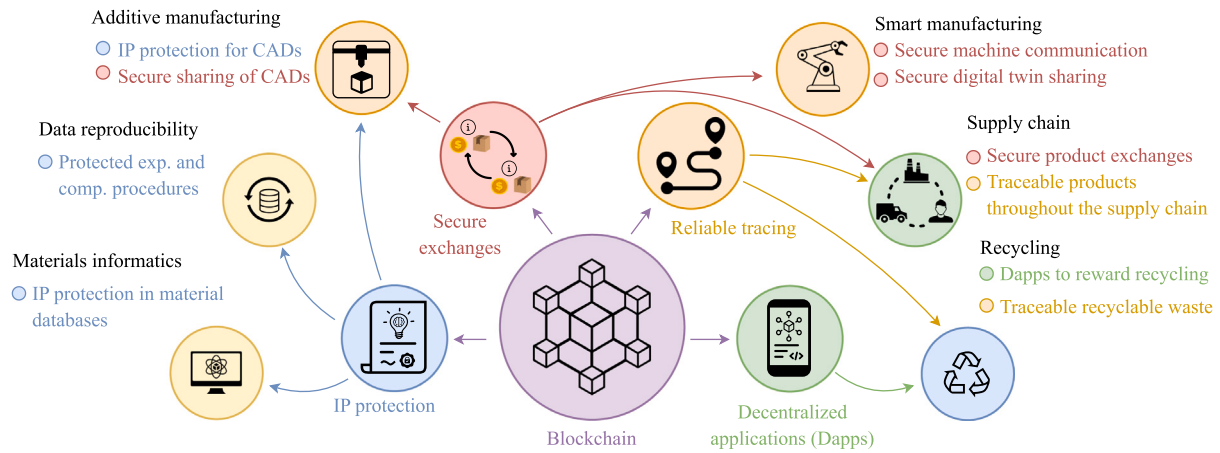


Fig. 5. Blockchain contribution to materials informatics, data reproducibility, AM, smart manufacturing, supply chains, and recycling.

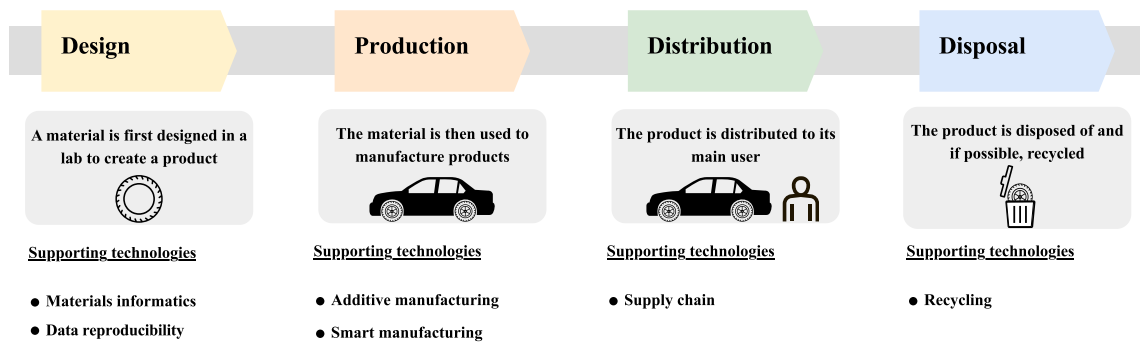


Fig. 6. Overview of the design, production, distribution, and disposal of products.

in a laboratory, it can be used to create various products that serve a purpose in society. The development of these products is then handled by manufacturing facilities specialized for rapid mass production. Through the use of advanced manufacturing techniques and novel ITs, manufacturing facilities have been able to create more efficient manufacturing processes. Further, such advanced technologies allow industries to collect great amounts of data that enable businesses to make informed decisions. For the production stage, we will discuss the areas of AM and smart manufacturing. These two topics were chosen due to their relevance in manufacturing schemes. AM facilitates the creation of complex products and smart manufacturing enables mass data collection and distribution within a factory.

3.2.1. Additive manufacturing

AM is widely regarded as an influential technology in the manufacturing space since it allows for a more sustainable, efficient, cost-effective, and decentralized manufacturing process. This technology fabricates products with complex geometries in a layer-by-layer fashion, producing a small amount of material waste [86]. Additionally, using CAD software, AM can print intricate products whose complexity is limited by human imagination. Furthermore, creating complex products and assemblies with AM requires fewer manufacturing steps than traditional manufacturing [87]. Moreover, AM allows factories to be closer to the consumers, which decreases the cost of transportation. As a result, it is possible to create shorter and more localized value chains, allowing for a more decentralized manufacturing process [86]. All of these aspects make AM an important innovation that can positively impact the manufacturing industry; in fact, it has been regarded as an enabler for the next generation of manufacturing.

Blockchain and AM: Unlike material informatics and data reproducibility, there is substantial research on the implementation of

blockchain in AM. To perform the keyword analysis, we searched the literature from the Scopus database using the keywords “blockchain” and “additive manufacturing”. Through this search, a total of 107 documents were found. Fig. 7 shows the keyword co-occurrence from the identified documents. From Fig. 7, we find that keywords like “intellectual property protection”, “data storage”, and “smart contract” appear along with “blockchain” and “additive manufacturing”. In addition, “supply chain management” and “industry 4.0” can be found. This reveals that studies focusing on blockchain and AM are interested in intellectual property protection as well as data storage. Similarly, blockchain and AM studies can be focused on supply chain and industry 4.0 implementations.

3.2.2. Smart manufacturing

Smart manufacturing is a concept that describes the next generation of manufacturing systems. In recent years, new manufacturing models have been conceptualized to tackle challenges such as the increased demand for personalized products [88,89]. Examples of such manufacturing schemes are described in Table 3 and include smart manufacturing, cyber-physical production systems (CPPS), Industry 4.0, cloud manufacturing, and social manufacturing [88]. While these models vary in definition, they all strive to use advanced technologies to reach greater personalization, automation, and sustainability in manufacturing industries [88,89]. In this paper, the application of novel technologies to improve manufacturing systems will be referred to as smart manufacturing.

Blockchain and smart manufacturing: A keyword co-occurrence analysis was performed to determine existing themes on studies related to the application of blockchain in smart manufacturing. We used Scopus to search for literature using the keywords “blockchain” and “smart

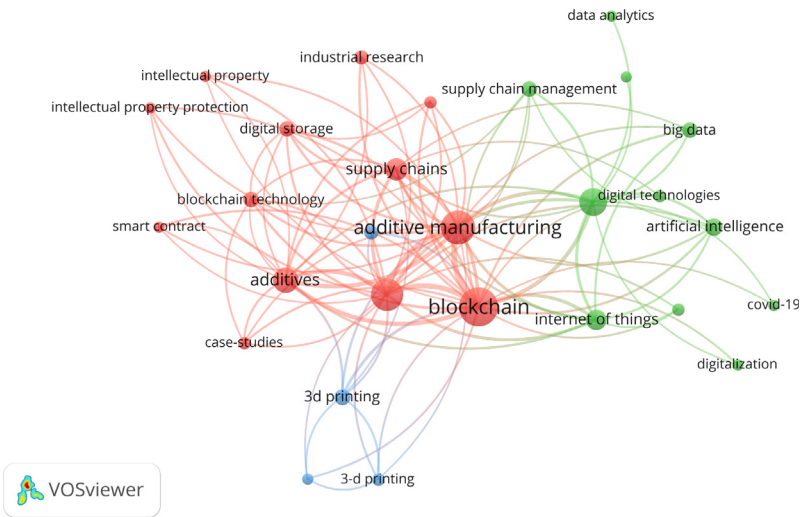


Fig. 7. Keyword co-occurrence from the literature in blockchain and AM.

Table 3
Summary of new manufacturing paradigms.

Manufacturing paradigms	Reference	Description
CPPS	[88]	The use of specialized cyber–physical systems to meet manufacturing services.
Smart manufacturing	[90]	The use of advanced technologies that can adapt to a changing environment.
Industry 4.0	[91]	The use of interconnected systems that facilitate automation and optimization in manufacturing.
Cloud manufacturing	[92]	Uses cloud services to organize manufacturing services based on customer’s demand.
Social manufacturing	[93]	Integrates ideas from social media through the creation of cyber–physical–social systems.

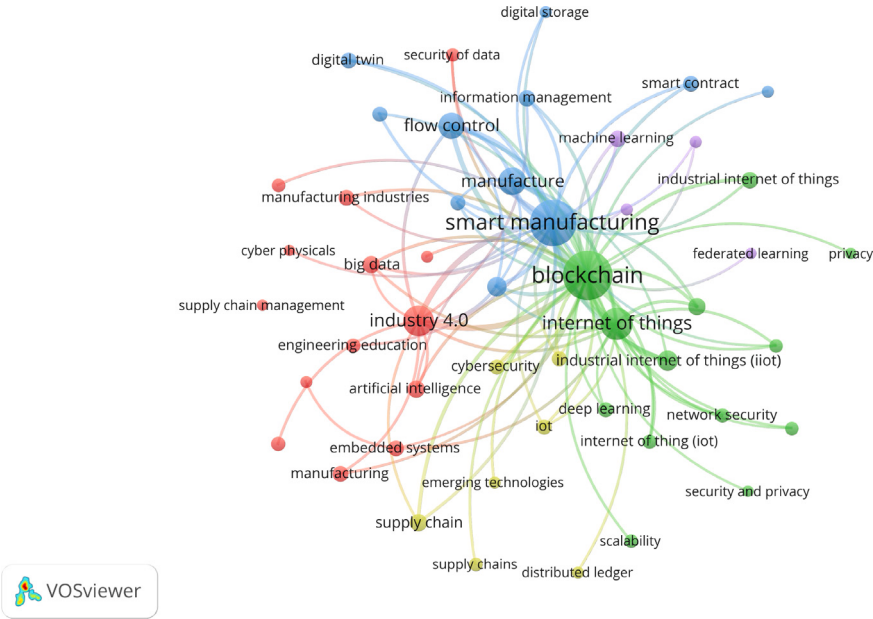


Fig. 8. Keyword co-occurrence from the literature in blockchain and smart manufacturing.

manufacturing”. After performing the literature search, we found 160 documents from which we created the co-occurrence map shown in Fig. 8. Fig. 8 reveals keywords such as “network security”, “cybersecurity”, and “security of data”. The appearance of these keywords reveal that studies on blockchain and smart manufacturing are interested in digital security. Similarly, the keywords pointing to IoT show that smart manufacturing and blockchain works focus greatly on IoT themes.

3.3. Distribution

The distribution stage investigates the processes in charge of taking products across supply chains. A supply chain is a series of interconnected entities that encompass suppliers, manufacturers, storage facilities, transportation services, and retailers, who are responsible for the development and distribution of a product to its user [42,44]. This

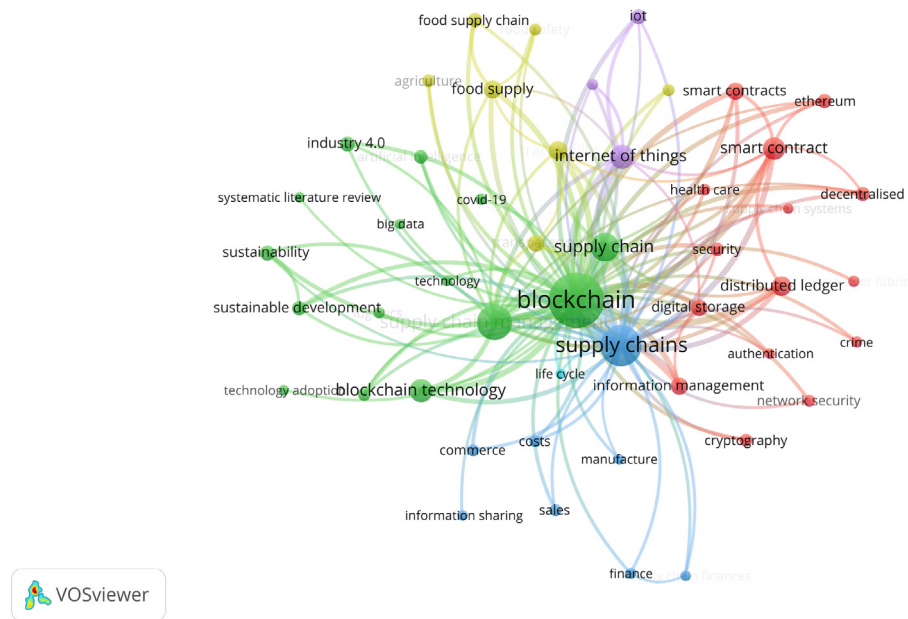


Fig. 9. Keyword co-occurrence from the literature in blockchain and supply chain.

process plays a significant role in society as it is the one in charge of giving consumers access to goods and services at the right time, place, and cost [94]. After a product is developed, supply chain entities become responsible for delivering the product from the manufacturing facility to the retailer/user. Even during product development, supply chain entities contributed by taking components across various industries to create complete products. Novel ITs can be utilized to enhance supply chain processes by improving traceability, transparency, security, and sustainability. Improving these aspects can reduce costs, increase trust, boost customer satisfaction, and further enable the next generation of manufacturing.

Blockchain and supply chain: There is extensive literature on blockchain and supply chain. Scopus shows 5212 papers on this topic. We conducted a keyword co-occurrence analysis to understand the trends in the blockchain and supply chain body of literature. Fig. 9 shows the co-occurrence map. Noteworthy keywords shown in Fig. 9 are “cryptography”, “security”, and “information management”. These keywords imply that studies on blockchain within a supply chain are interested in information security solutions. Also, we can find keywords such as “sustainability”, “traceability”, and “transparency” which reveal that these studies are seeking to improve various aspects of a supply chain through blockchain.

3.4. Disposal

The disposal stage deals with the procedures required to dispose of materials after their use. In this stage, we will discuss recycling as it is an important component of product disposal that aims to regain the value of disposed materials and maintain them in the loop [9]. Recycling is a method used to reduce the environmental impact of materials by processing and repurposing them after their use [25]. Recycling is beneficial for the environment and human health as it reduces greenhouse gas emissions and limits contamination in natural environments.

Blockchain and recycling: We conducted a keyword co-occurrence analysis to understand the trends found in blockchain and recycling literature. Using Scopus and the keywords “blockchain” and “recycling”, we found 157 studies. Fig. 10 reveals the keyword co-occurrence map and presents keywords such as “plastic recycling”, “plastic waste”, and “plastic products”. These keywords imply that studies working on blockchain and recycling show interest in plastic waste.

4. Challenges

In this section, the challenges in the design, production, distribution, and disposal stages of products will be introduced. Specifically, Section 4.1 presents the challenges in design by focusing on the areas of materials informatics and data reproducibility. Section 4.2 reveals the challenges in production by focusing on the areas of AM and smart manufacturing. Sections 4.3 and 4.4 introduce the challenges in distribution and disposal, respectively.

4.1. Challenges in design

4.1.1. Materials informatics

Data availability, quality, and quantity are paramount for materials informatics as it relies on the performance of data-driven models. Without sufficient data, machine and deep learning models will not deliver accurate results, which burdens the use of these techniques to study materials. While there currently exists extensive data on numerous materials, this data often lacks the appropriate metadata or is not made publicly available. As a result, this area faces challenges regarding the lack of metadata and data sharing.

• *Metadata*: Metadata refers to the information that describes scientific data. It can include the details regarding the asset from which the data was gathered, the experimental or computational methods used to obtain the data, the authors who published the data, and the characteristics of the digital file [78]. This information helps researchers understand the background of scientific data, which allows them to better interpret the dataset and use it in their work. Additionally, adding adequate descriptors to scientific data makes the dataset findable by both humans and computers, which increases the dataset's impact. In contrast, omitting the creation of adequate metadata will affect the dataset's impact as it will be difficult to find and practically unusable. Without metadata, the scientific community would be unable to determine the dataset's relevance or provenance, which may limit its application in research. Moreover, it is beneficial for both the authors and the scientific community that scientific data is accompanied by its corresponding metadata. Nonetheless, significant scientific data lack proper characterization and there is currently no metadata standard [57,78,80,95].

- *Adoption of data sharing practices:* Encouraging researchers to share their data is important for the success of materials informatics. Since

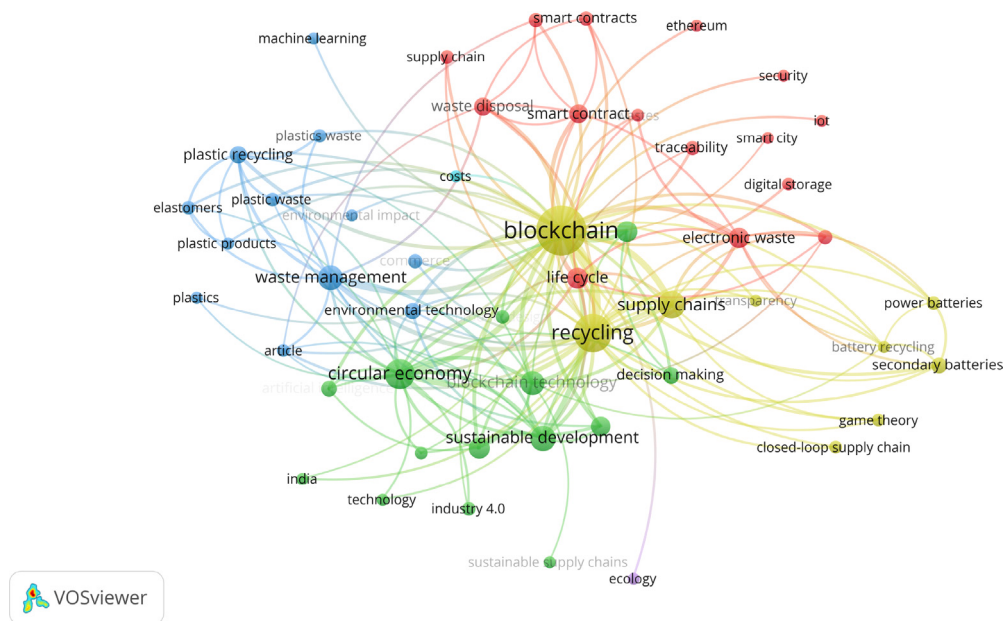


Fig. 10. Keyword co-occurrence from the literature in blockchain and recycling.

materials informatics depends on the availability and quantity of data, it will benefit from the data provided by the scientific community. The larger the amount of available data, the better the performance of data-driven models. Additionally, data sharing allows for increased collaboration within the scientific community. For instance, a researcher's experimental data can help computational scientists verify the applicability of their computational model [96]. Moreover, through the shared data, researchers would be able to advance their work, increasing the number of valuable findings in materials science. Due to these advantages, existing materials databases have implemented the data sharing feature to their platform. This is seen through databases such as The Materials Project [97], NOMAD [98], and ioChem-BD [99]. Despite the benefits of data sharing, many researchers are reluctant to share data due to the concern of getting scooped, IP infringement, data misuse, and not getting proper credit [57,96,100].

4.1.2. Data reproducibility

Currently, the importance of reproducible and trustworthy research is highlighted by the demand to use existing data to power future discoveries. Moreover, this data needs to be reproducible to verify its correctness. However, reproducibility is not as widespread as it should be.

Unreproducible studies: The reproducibility of academic studies has come into question after it was revealed that a large amount of them could not be reproduced [83,101]. In fact, a 2016 study that surveyed researchers across various disciplines, including chemistry, biology, physics and engineering, medicine, and earth and environment, found that more than 70% of them were unable to reproduce other researchers' studies [101]. Additionally, there have been research papers that have been punished due to having unreproducible studies or forged data [85]. There are many factors that can cause such irreproducibility. For example, the use of specialized techniques [82,101] or the use of complex computational processes [81] can affect the ability of others to replicate results in experimental and computational studies respectively. In addition to these two factors, poorly described methodologies and the absence of data, software, and tools have affected the reproducibility of both computational and experimental works [81,82,101,102].

4.2. Challenges in production

4.2.1. Additive manufacturing

The use of CAD makes AM digital in nature. Moreover, the digital nature of AM exposes it to several security challenges that can lead to data tampering and IP theft.

Data tampering and IP theft: AM relies on a series of digital files created from CAD software that contain all the instructions for AM machines to manufacture a product. Files such as stereolithography (STL) and geometric code (G-code) are of great importance. If these files are compromised by malicious entities, they can cause great damage to companies or organizations. For instance, through the design files, malicious entities can create counterfeit products using their own AM machine. Alternatively, they can make detrimental changes to the design files that result in defective manufactured products [1,33]. These two problems are examples of possible attacks that can affect the revenue and reliability of a business. To lower the possibility of these attacks, effective security measures must be used in AM so that data tampering and IP theft are prevented [1].

4.2.2. Smart manufacturing

The implementation of various innovative technologies, such as cyber-physical systems, AI, edge computing, fog computing, cloud computing, and IoT, work together to enable the future of manufacturing [89,103]. For instance, cyber-physical systems allow factory devices to interact with the physical and digital world through sensors collecting data, communication networks sharing and processing data, and actuators turning processed data into actions. AI can process the data while edge computing, fog computing, and cloud computing can provide factory devices with computational resources. IoT facilitates the execution of these processes by providing a network for the devices to communicate. In factories, the network is the industrial internet. Through these technologies, manufacturing industries can upgrade factories to smart factories where machines with a high level of coordination can collect large amounts of data, communicate with other machines or humans, and adapt to different situations [89,103].

Even though introducing IoT to manufacturing provides a useful communication network within factories, digitally interconnecting factory devices through the internet introduces vulnerabilities to cyber attacks [35,39,104].

Security: Relying on the internet for communication requires enterprises to prepare against cyber attacks, such as man-in-the-middle or denial-of-service attacks, that threaten the reliability of the factory as a whole. In the past, various industries have been the subject of cyber attacks on factory data or devices [105]. For example, in 2019 an aluminum company called Norsk Hydro was attacked by LockerGoga, a ransomware that encrypted the company's data and requested a ransom for decryption [105,106]. Manufacturing data contains sensitive information that is valuable to the company. To keep this data trustworthy and reliable, it must be protected against attacks that seek to compromise the data. Moreover, to implement smart manufacturing, effective cybersecurity measures must be applied to guarantee a smooth manufacturing process [39,104,105].

4.3. Challenges in distribution

Supply chains face several issues related traceability, transparency, and trust. These issues affect the overall supply chain by discouraging the collaboration between supply chain entities.

- **Traceability:** Over time, supply chains have increased in complexity due to the growing number of participants and the expansion across the globe [42,107]. With a large number of components over large distances, it is difficult to correctly keep track of products across a supply chain [8,42]. As a result, it is challenging to determine the provenance of a product, which is crucial when trying to identify a counterfeit or the origin of a defective product [8,42,44]. Thus, supply chains need to find a solution to enable efficient product traceability and accessible provenance information.

- **Transparency:** Supply chains do not only benefit from improved traceability, but they can also benefit from increased transparency [8, 42,44,107,108]. Transparency is an important feature in a supply chain as it is often demanded by customers and entities within the supply chain [42,107]. Accessible and reliable information about a product's origin, quantity, demand, and environmental impact can help both consumers and producers make informed decisions and plan ahead. For instance, this information can help customers determine the product's carbon footprint, which influences their purchasing decisions [8]. On the other hand, this information can help businesses understand the supply and demand of a product, which helps them plan ahead [41]. Without transparency, customers may oppose products and businesses may be unable to accurately predict future events [41]. Furthermore, the lack of transparency burdens efficient supply chain operations and could decrease the number of customers.

- **Trust:** To achieve effective communication between supply chain parties, there must be sufficient trust between them. However, trust is difficult to achieve in current supply chains potentially due to supply chain participants treating each other as competitors [41]. The lack of trust as well as the individualistic behavior increases the opacity in the supply chain. In turn, supply chain participants will have difficulty forecasting events such as future customer demand [41]. Even if supply chain participants shared their data, other participants would not completely trust the data as the reliability of such data is not guaranteed. If the objective is to share this data with customers and other supply chain stakeholders, the data must be trustworthy. This is challenging to achieve through a centralized data storage system since centralization generates problems that affect the authenticity of the data. Relying on a single entity to manage the data increases the risk of manipulation and forgery [42,107]. Additionally, serious damage can occur if this entity is ever compromised or shuts down abruptly [107].

4.4. Challenges in disposal

Recycling is a community effort, which requires producers, consumers, and disposal entities to contribute in order to gain the benefits from recycling. However, there are currently challenges that limit the

participation of these parties. These challenges involve the cost of recycling and the contamination in the recycling stream.

- **Cost of recycling:** The cost of recycling varies from material to material. In some cases, recycling offers a cost-effective and environmentally friendly solution to reuse materials, avoiding the need to extract or manufacture more of them. However, there are other materials in which recycling is more expensive than creating virgin materials. This is the case for plastic, where recycling requires extra work and energy to implement, which leads to an increased cost. The higher price is partially due to the work needed to separate the waste materials and the energy needed for the recycling process. In addition, it is cheaper to dump or incinerate waste rather than recycling it [28]. As a result, plastic is rarely recycled and often ends up in landfills or in waste-to-energy facilities.

- **Contamination in the recycling stream:** Contamination occurs when recyclable materials are mixed with other recyclable or unrecyclable waste. Such contamination is detrimental as it reduces the recoverability of certain materials and could even cause damage to equipment in recycling facilities [109]. Moreover, to effectively recycle it is necessary to reduce contamination by organizing recyclable waste into separate groups for each distinct recyclable material. However, separating waste is difficult since there are several different types of materials and multiple materials can be used in a single product. In addition, separating waste requires participation from the public, who may not be willing, or able, to rigorously organize their waste. To increase public participation, many countries use a single stream recycling system, where all the recyclable waste is grouped into one trash bin. Nevertheless, in this recycling system, contamination is common and it requires material recovery facilities to do extensive work in separating each material, which leads to higher recycling prices and lower revenues for these facilities [109].

5. Blockchain implementation

This section presents the implementation of blockchain in the design, production, distribution, and disposal stages of a product. Specifically, Section 5.1 shows blockchain implementation on materials informatics and data reproducibility. Section 5.2 reveals blockchain implementation in additive manufacturing and smart manufacturing. Sections 5.3 and 5.4 introduce blockchain implementation in distribution and disposal, respectively.

5.1. Blockchain implementation in design

5.1.1. Materials informatics

Blockchain is specially designed to manage data from multiple sources. As such, blockchain can be used to support existing material databases and the development of new collaboration platforms.

- **Blockchain for existing material databases:** Existing material databases can adopt blockchain to manage and protect metadata. It is important to keep metadata secure and immutable since it contains the authorship information of scientific data. To ensure researchers will have a verifiable and reliable way to prove their authorship to the submitted data, the dataset's metadata can be stored in a blockchain system. Then, the metadata will become unchangeable and secured against malicious activity like tampering. In this way, existing materials databases can keep their data storing and sharing infrastructure and leverage blockchain to further protect the researcher's IP, as shown in Fig. 11. To link the scientific data stored off-chain to the metadata stored on-chain, the metadata can include the hash value of the original scientific data. In this case, if either the scientific data or metadata is modified, it can be easily identified through the blockchain. Using this blockchain application, it is possible to tackle IP infringement, one of the factors that affects data sharing. Removing the IP concern will encourage more researchers to share their data with the scientific community via open material databases. The use of blockchain to

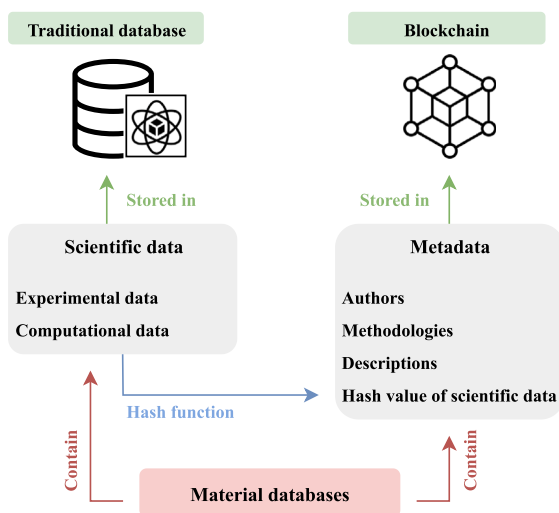


Fig. 11. Materials science databases using blockchain to store metadata.

improve data sharing in material databases has also been proposed in [56,57]. In these works, data sharing platforms are developed for materials science that utilize blockchain to solve data management and security problems.

- **Decentralized electronic collaboration platform:** Blockchain can support the creation of platforms that foster the collaboration between scientists and encourage scientists to share data without an intermediate regulatory party [56,110]. Ideally, everyone should have the opportunity to access the available materials data and contribute to the databases. To this end, a decentralized environment where no single entity controls the entire dataset is beneficial. Blockchain enable such a decentralized environment. Additionally, in a community-driven platform, it could also be possible for researchers to help each other provide adequate scientific data or metadata. For example, Bob and Alice are materials scientists and Bob would like to use the data Alice uploaded, but Alice's data is not well characterized. In this case, the platform can allow Bob to comment on Alice's data and let her know how she can improve her metadata so that her data is useful to others.

A blockchain-based collaboration platform can also take advantage of digital tokens to encourage scientists to share data. The idea is to reward researchers for contributing to the database using digital tokens that are managed by a blockchain system. Finally, governing organizations can get involved by proposing awards or recognition to researchers whose data had the most impact [96]. In this area, blockchain can track downloads or citations and use those as a reference to determine how impactful the data was. Rewarding impactful data can indirectly promote the development of good metadata since scientific data that is well described will have a higher chance of being utilized by other researchers.

5.1.2. Data reproducibility

Blockchain can be used to increase the reproducibility of both experimental and computational data. We provide examples of how blockchain can facilitate reproducibility below.

- **Computational data reproducibility:** It is possible to take advantage of an Ethereum virtual machine to perform computational simulations [84]. The Ethereum virtual machine is essentially a virtual computer powered by the various computers that contribute to the blockchain network. This type of virtual machine was developed by Ethereum [62] to execute smart contracts that are written on a Turing-complete programming language called Solidity. Through Solidity, computational scientists can write programs that run mathematical simulations. [83] demonstrated that an Ethereum virtual machine could

store and perform quantum chemistry simulations through molecular dynamics. By performing this simulation through an Ethereum virtual machine, they could store the exact parameters and code used for a molecular dynamics simulation and repeat it at the Ethereum blockchain. Because of the properties of blockchain, the work on the virtual machine is immutable and can be exactly repeated by whoever has access to the virtual machine. If researchers take part in performing simulation through an Ethereum virtual machine, it can guarantee that future computational works are reproducible by anyone who has access to the blockchain.

- **Experimental data reproducibility:** Experimental studies are challenging to reproduce since they require a great amount of tools and expertise. In experimental studies, simply uploading a description of the tools and methods used during experimentation to a blockchain system is not enough to guarantee the reproducibility of the study. Inspired by the advancement of robotics, [85] designed a physical platform where robots can automatically execute experiments based on instructions stored on a blockchain. The idea is to have researchers submit the instructions that describe how their experiment was performed to a blockchain. Then, the machine would verify the results of the experiments by following the set of instructions. Through this idea, researchers of various backgrounds could reproduce existing works, increasing the trust in experimental studies.

5.2. Blockchain implementation in production

5.2.1. Additive manufacturing

Blockchain can support additive manufacturing by providing methods to quickly detect unauthorized manipulation and protect the IP of AM design files.

- **Data tampering detection:** Using a combination of hash functions and blockchain's immutability, it is possible to detect if STL [33] or G-code [5] files were tampered with before a product is manufactured. This is accomplished by storing on the blockchain the hash value of the original STL or G-code file [5,33]. It is not necessary for the blockchain to store the AM design files, instead it can only store their hash values. At the printing step, the AM machine can check if the hash value of the file that will be printed matches the hash value of the original file, which was stored in the blockchain [5,33]. The machine would only print files whose hash value coincides with that of the original file. If there are any unwanted changes to the file, the hash value will reflect it. This method is shown in Fig. 12.

Ideally, the file that will be printed should be the same as the original file. By comparing the hash values of the current file with that of the original file, it is possible to identify if the file had been manipulated. Tampering with the original file's hash value can also be detected since it is stored in the blockchain. If any data is altered in the blockchain, it will be immediately exposed by comparing the hashes of the blocks in the blockchain. These verification methods, which were demonstrated by [5,33], demonstrate how blockchain can be applied to create a scheme that quickly detects data tampering and prevents manufactured products from having deficiencies due to malicious activity.

- **IP protection:** Additionally, blockchain can protect against IP theft through smart contracts. Smart contracts are valuable for IP management and the licensing of AM designs. When a company or individual licenses CADs to an AM service provider, it is possible for the latter to violate the license by either copying/sharing the design or by printing more than the allowed amount [31]. This would result in the creation of counterfeits that go against IP rights, which can cause the original designer to lose revenue. To overcome this issue, licenses could be realized through smart contracts [31,32,34,111,112]. These smart licenses would contain all the information from the original license and enforce the execution of the license by both parties. Fig. 13 presents some of the contents in the smart contract a designer could use to license their design to a manufacturer.

Table 4
Examples of works taking advantage of blockchain to improve AM.

Blockchain in AM		
Objective	Reference	Description
Tampering detection	[5]	Protected G-code files by using blockchain and an asymmetry encryption technique.
	[33]	Protected the integrity of AM designs by storing the STL-file's hash value in a blockchain.
Intellectual property protection	[31]	Developed a set of smart contracts to check for tampering and to issue certificates of authenticity.
	[32]	Designed a blockchain system where designers and manufacturers could share their services.
	[111]	Proposed a blockchain system where designers can license designs through smart contracts.
	[113]	Presented a blockchain-based AM platform using trusted printers and digital licenses.
	[115]	Designed a smart contract on Ethereum for AM parts to protect IP and increase traceability.

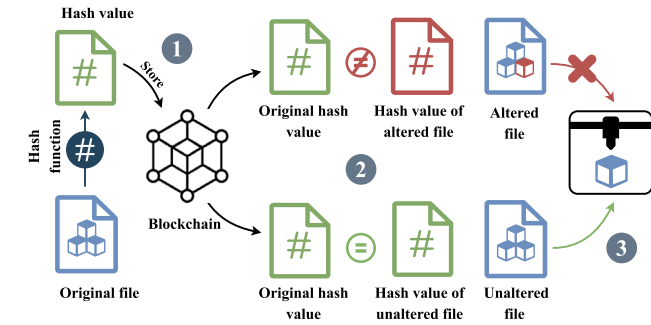


Fig. 12. Secure STL, G-code, and CAD files for AM using blockchain. (1) Calculate the file's hash value and store it in the blockchain; (2) Compare the file's hash value with the one stored in the blockchain; (3) Print the file if its hash value matches the one stored in the blockchain [5,33].

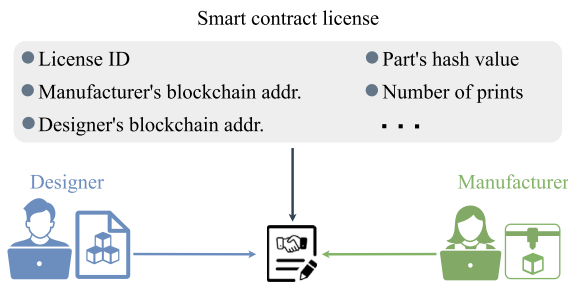


Fig. 13. Licensing of designs through smart contracts [31].

Smart contracts can also simplify the detection of counterfeits. [31] proposed the use of certificates of authenticity to identify counterfeits. This certificate would be issued by the smart contract to the prints that were allowed in the license. Any prints outside the license's agreements, would not have the certificate, which simplifies the verification of counterfeits. Moreover, blockchain and smart contracts can provide verifiable proof of IP [1,7,31,32,34,111–114]. Overall, smart contracts enabled by blockchain can further protect IP and control the distribution of AM designs. Other frameworks that apply blockchain in AM can be found in Table 4.

5.2.2. Smart manufacturing

Smart manufacturing systems require effective data management systems since they produce large amounts of data. Blockchain can provide security and storage resources in smart manufacturing to facilitate the communication between machines, the automation of processes, and the management of digital twin data.

• **Machine-to-machine communication:** Blockchain can support the interaction between machines by providing them with a safe communication environment where humans and machines can trust the information collected by other devices within the factory [39,116]. Such an environment can be achieved by having factory devices be part of a blockchain system. Being part of a blockchain would allow factory

devices to reliably store relevant data and sign it using digital signatures. By letting these devices sign their own data, other devices within the network can verify that the information comes from a trustworthy node [36,38,39]. For this application, a permissioned blockchain would be useful as it can restrict the participants of the network to only manufacturing equipment. In this way, no unwanted party could easily intervene with the collection and distribution of data within an advanced factory. An example of how blockchain can be integrated to aid the interaction between machines is demonstrated through [117], who utilized of a consensus algorithm called Proof-of-Stake and a private blockchain. This approach not only secured the collected data but also controlled the flow of data generated by the various factory machines. Table 5 shows existing works that utilize blockchain to enable secure device interconnection in smart manufacturing.

• **Process automation:** Smart contracts can be implemented to further automate various factory processes using the data collected from manufacturing equipment [118]. For example, smart contracts can be written to monitor the data from a certain instrument to determine if it will fail in the future [119]. If the instrument's data goes beyond a certain threshold, the smart contract will trigger and alert the factory. As such, a smart contract can facilitate the detection of faulty devices in a factory [89]. Additionally, smart contracts could monitor manufacturing data to determine if a facility is following the expected guidelines. If not, the smart contract can issue penalties or warnings to the respective company [38]. Smart contracts can also define robotic control logic to command robots in a factory, as shown by [120]. Utilizing smart contracts to automate processes is beneficial for factories since these contracts execute automatically and are tamper-proof. Therefore, factories can ensure processes will execute as intended.

• **Digital twins:** Blockchain can be used to manage the creation and development of digital twins in smart manufacturing. A digital twin is a digital representation of a physical object or process [121]. Using a digital twin, manufacturers can monitor the development and operation of products or machines through a digital counterpart. Such virtual representations allow stakeholders to visualize the development of a product and facilitate the collaboration between producers and consumers. To effectively collaborate, it is crucial to ensure the security of digital twins and guarantee their reliability [122]. To this end, blockchain can be implemented to manage the digital twin data so that it is safe and trustworthy. Table 5 shows frameworks that implement blockchain to ensure the security and shareability of digital twins.

5.3. Blockchain implementation in distribution

To minimize the lack of traceability, transparency, and trust in supply chains, blockchains can be implemented to record product-related data. Recording such data on a blockchain allows the participants on the system to reliably view the product throughout its life, enabling product traceability.

• **Product traceability:** Traceability can be achieved by recording information about the product throughout the supply chain. Information like the history of the product's location, custody, and status are useful to track the development of the product and obtain traceability. A blockchain system can be created to collect product-related data so

Table 5

Examples of works taking advantage of blockchain to improve smart manufacturing systems.

Blockchain in smart manufacturing		
Objective	Reference	Description
Securely interconnecting devices	[37]	Used edge computing and blockchain to distribute computational power and connect devices.
	[116]	Provided a trustworthy space for IoT devices to communicate using a public blockchain.
	[119]	Created a blockchain-based mobile crowd sensing system to collect data within a factory.
	[123]	Integrated blockchain and deep reinforcement learning to collect and share data in industrial IoT.
	[124]	Used blockchain to enhanced security, privacy, and decentralization within a smart factory.
Digital twin management	[125]	Increased the efficiency and security for industrial IoT using a specialized blockchain.
	[121]	Created a quantum resilient blockchain system named Twinchain to manage digital twin data.
	[122]	Constructed a blockchain-based framework for securing digital twins and to reliably share them.
	[126]	Proposed a blockchain system to solve challenges in data storage and sharing for digital twins.
	[127]	Implemented blockchain to facilitate the creation of digital twins in smart manufacturing.

Table 6

Examples of works taking advantage of blockchain to improve supply chain.

Blockchain in supply chain management		
Objective	Reference	Description
Improving traceability in supply chains	[2]	Proposed a specialized blockchain to trace products and detect counterfeiting attacks.
	[6]	Developed a scheme to track products using data from IoT devices stored in a private blockchain.
	[40]	Printed QR codes with specialized polymers on products that link the product to a blockchain.
	[41]	Integrated blockchain to a supply chain and simulated its performance to demonstrate the benefits.
	[128]	Presented a plan for recording the ownership of a product through the supply chains.
	[130]	Created a sustainable blockchain to guarantee the security of a hazardous material supply chain.
	[131]	Utilized blockchain in a plastic pipe manufacturing company to prevent counterfeiting.

that such data is open to all participants and secured against manipulation [2,6,107,128]. The participants of the network would be the supply chain entities who will gain a set of public and private keys to sign data. A method to implement blockchain traceability in a supply chain is by having the blockchain keep a record of ownership of the product [2,128]. In this way, a blockchain can track the custody of a product as it travels across a supply chain. To write the change in ownership on the system, a smart contract could be implemented, where the contract would update the ownership of the product after the entities who are exchanging the product provide their digital signatures to the smart contract [128]. Additionally, the blockchain provides a timestamp for every transaction, which can be used to identify the chronological chain of ownership [128].

To further improve traceability and transparency, supply chains can use blockchain in conjunction with novel ITs. For example, industries can use a combination of advanced sensor and communication technologies to collect meaningful data on a certain product and use blockchain to store the data or the hash of the data so that it is secured. Sensors such as a SensorTag or global positioning system (GPS) can be used to record the environmental conditions (e.g., temperature, humidity, pressure, etc.) of the product as well as its location [6,107]. Through IoT and smart contracts, the sensors can automatically store their data on a blockchain system or an external database, like InterPlanetary File System (IPFS) [129]. Then, the recorded data can be made accessible through smart tags attached to the product like radio frequency identification (RFID) tags, near-field communication (NFC) tags, or quick response (QR) codes [107]. As such, it is possible to trace goods across the chain, allow access to the product's data, and make the data tamper resistant through blockchain, as shown in Fig. 14. This method is useful for products that require specific travel requirements, like food or medicine, since blockchain can ensure that these requirements were met while they pass through the supply chain. In fact, smart contracts could be leveraged to alarm the supply chain entities if any conditions are not met. More works on this subject can be found on Table 6.

5.4. Blockchain implementation in disposal

Blockchain can be applied in two separate ways to support recycling. Blockchain can be used to store waste exchanges and monitor recyclable material production.

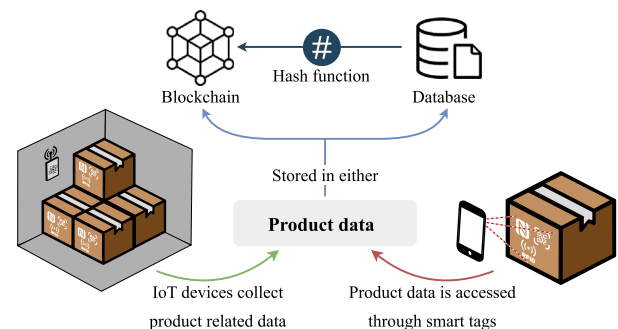


Fig. 14. Sensor and communication technologies collect product data that can be accessed through smart tags (QR code, RFID, or NFC). The product data is stored either directly on the blockchain or on a separate database, whose hash value gets stored in the blockchain.

- **Blockchain can be used to keep records of transactions made while buying or selling recyclable waste:** A method used to encourage recycling is adding value to recyclable waste. In this method, recyclable materials, like plastic bottles, will acquire monetary value that can be obtained by selling the material at a designated facility or by disposing of it in an indicated trash bin. Providing such monetary incentives can motivate the public to better separate and organize misplaced waste. To prevent fraud, this method can leverage blockchain to create a platform that records the transactions made when exchanging recyclable waste for goods. Using blockchain, organizations can keep track of the amount and type of waste collected, as well as the waste collectors and their rewards in an immutable fashion. In some existing applications, the rewards are digital tokens that are tracked through the blockchain and can be exchanged for goods or services [132]. In other applications, the rewards are based on a deposit return scheme, where an extra fee that is paid for a product is returned after the product has been correctly disposed of [133]. Smart contracts and smart trash bins can also be used to further automate this process and remove the need for human involvement [29,53].

- **Blockchain can be used to monitor the production of recyclable products:** The responsibility of recycling belongs not just to the consumer, but also to the manufacturer. To limit the quantity of unrecoverable

Table 7
Examples of works taking advantage of blockchain to improve waste recycling.

Blockchain in recycling		
Objective	Reference	Description
Supporting recycling	[30]	Applied AI to separate plastics and used blockchain to store plastic waste data.
	[54]	Used blockchain and AI to create a system that identifies waste and suggests ways to recycle it.
	[26]	Developed a model using blockchain that can assigning a credit to waste based on its recyclability.
	[29]	Created smart trash bins capable of organizing plastic waste from on a certain QR code.

waste, businesses should strive to create products that could be easily recycled. To this end, [24] proposed the creation of a plastic credit following the idea of carbon credits. Through this credit, governing agencies would allocate businesses a limited amount of possible unrecyclable products they could manufacture. Further, businesses could buy or sell these plastic credits to fit their production demand. To keep this process transparent and trustworthy, blockchain is used to monitor the flow of these credits across businesses. This application would use a consortium blockchain whose participants include raw material suppliers, manufacturers, non-governmental organizations, or governments [24]. All of these organizations would play a part in the blockchain to control and keep track of the generation and allocation of credits as well as the use of recyclable and non-recyclable materials. In this way, the plastic credit scheme in conjunction with blockchain can incentivize the creation of recyclable products while diminishing the possibility for malicious activity. Table 7 shows some examples of blockchain applications to aid in recycling.

6. Blockchain benefits

In this section, the benefits of blockchain in the design, production, distribution, and disposal are discussed. Specifically, Section 6.1 provides the benefits of blockchain in materials informatics and data reproducibility. Section 6.2 presents blockchain benefits in additive manufacturing and smart manufacturing. Sections 6.3 and 6.4 show blockchain benefits in distribution and disposal, respectively.

6.1. Blockchain benefits in design

6.1.1. Materials informatics

To maximize the impact of material data, the data should follow the FAIR principles [134], that is, the data should be Findable, Accessible, Interoperable, and Reusable (FAIR). By following these principles, material scientists will be able to easily disseminate their data and take advantage of the data from other researchers. Notably, an important part of this vision is the scientific community as it is their data that will power the research of the future. Since the scientific community is the basis for a FAIR data infrastructure, it is essential to convince them that data sharing can improve modern science and engineering [80]. However, the hurdles like getting scooped, IP infringement, data misuse, and not getting proper credit, need to be addressed as they prevent the participation of researchers.

Blockchain can contribute to materials informatics by removing the hurdles that discourage material scientists from sharing data. In particular, blockchain can further protect IP, addressing IP concerns researchers may have by sharing their data. This blockchain application could increase the participation of researchers in the development of material databases. Overall, blockchain can improve the availability of data by encouraging more researchers to share, which in turn further enables the application of data-driven methods to discover novel materials.

6.1.2. Data reproducibility

Through blockchain it is possible to ensure the reproducibility of academic studies by advancing the use of metadata. Metadata describes

the details of a certain study, which can take the form of code in computational science or instructions in experimental work. Blockchain can enhance metadata by allowing any code or instructions to be accessible, executable, and repeatable by anyone who has access to the blockchain. Furthermore, by taking advantage of blockchain virtual machines or advanced robotics, blockchain can be used to detect if any data was forged and ensure the reproducibility of experimental and computational data. Additionally, due to the security and immutability blockchain provides, the use of blockchain to enable these applications contributes to increasing the trust in scientific literature. Material databases can also leverage these ideas to enable the reproducibility of shared experimental or computational data.

6.2. Blockchain benefits in production

6.2.1. Additive manufacturing

Blockchain can provide the tools to build frameworks that increase the security in AM. Data tampering can be quickly detected through blockchain and AM design files can be further secured [5,33,135]. This is possible since blockchain can be used to protect against attacks that seek to manipulate CADs and further prevent the creation of counterfeits [1,5,33]. Furthermore, blockchain contributes to make printed products reliable and allows companies to verify that the product is authentic and unaltered. Blockchain technology can also support supply chains to facilitate the traceability of AM components, which will allow buyers to verify that the components came from the original manufacturer [115,135]. In addition, by ensuring the reliability of CADs, the use of blockchain in AM can further enable novel technologies like digital twins [136]. In summary, blockchain can help AM by providing a mechanism to solve data security challenges that relate to the digital assets created in AM.

6.2.2. Smart manufacturing

The application of smart manufacturing is beneficial in many material industries as it allows them to take advantage of the data generated within the factory. Industries could further automate and optimize processes through smart manufacturing. The drive to implement smart manufacturing is already seen in the semiconductor industry, where the seamless collection and distribution of data can predict process failures and future maintenance [137,138]. Similar to the semiconductor industry, the use of smart manufacturing has been explored for industries that involve polymers [139], ceramics [140], metals [141], and composite materials [142]. To further enable the utilization of smart manufacturing, blockchain can help create more robust manufacturing systems.

Integrating blockchain into smart manufacturing systems can make them more fault-tolerant. Firstly, it would be difficult for attackers to modify manufacturing data. This data would be stored in the blockchain, where a copy of the blockchain is stored across various devices and any changes on the distributed ledger are quickly identifiable. It is also difficult for attackers to submit erroneous or inflated data to the blockchain since only previously authenticated devices can write information to the blockchain. Submitting false data would require the attacker to impersonate a validated device, but that would need them to first calculate the device's private key, which is needed to sign data [123]. In addition, using a decentralized system like blockchain prevents the possibility of a single point of failure

that is displayed in regular database-based data sharing [123]. This implies that, even if a machine fails, it does not prevent the rest of the machines from working normally and keeping a distributed reliable ledger [123]. Blockchain systems have been developed for smart manufacturing and have shown increased protection against other types of attacks such as Distributed Denial-of-Service (DDoS) and Sybil attacks [116,119,123–125]. Moreover, implementing blockchain into smart manufacturing secures manufacturing data, which promotes the interaction between machines and increases the reliability of the manufacturing system [143].

6.3. Blockchain benefits in distribution

Blockchain can provide the tools to enable effective and reliable traceability of products across a supply chain. With blockchain, it is possible to manually or automatically record the locations the product has passed through while protecting this information from manipulation. Using this information, businesses can create a verifiable trail that will show a product's provenance on demand, which is helpful to quickly identify the source of an inadequate product or to verify the origin of a product. Further, blockchain can assure the authenticity of related product data and guarantee the data was uploaded by a reliable node in the supply chain through cryptographic signatures. In addition, all this information can be made available to customers to satisfy their demand. Moreover, blockchain can increase trust in a supply chain since it guarantees the legitimacy of supply chain data. As a result, stakeholders are more willing to interchange data and use it to create a more efficient supply chain process.

Utilizing blockchain can also facilitate the detection of counterfeit products in a supply chain. To check if a product is counterfeited, supply chain entities can look at the product's provenance, which should be recorded on the blockchain. By looking at the product's record on the blockchain, stakeholders would be able to verify if the product has followed the designated steps of the supply chain. Otherwise, if the product's record is not found, it indicates that the product is a counterfeit. Additionally, blockchain schemes can be developed to detect if a product's tag has been cloned and if the product's information has been altered [2]. As a result, the difficulty for malicious entities to create and sell counterfeit products will greatly increase.

The application of blockchain to supply chains can be extended to waste management systems. Similar to supply chains, many parties are involved in waste management. To facilitate their collaboration, a trusted database where every member could read and write information about waste would be beneficial. By utilizing blockchain, it would be possible to track materials even after they leave the trash can. In this way, stakeholders can ensure that waste reaches the correct processing plant.

6.4. Blockchain benefits in disposal

Effective waste separation is essential to recover waste materials since it reduces contamination in recycling streams. Blockchain can support waste separation incentive schemes by making them reliable. Making this process more trustworthy encourages more and more people to be part of waste separation incentive schemes. In turn, organizations can collect and organize a large amount of misplaced recyclable waste while promoting for future recyclable waste to be correctly disposed of. Existing initiatives like plasticbank, an organization that encourages the collection of plastic waste with the support of blockchain, have already collected over 77 million kilograms of plastic waste [132]. These initiatives show that honest waste collection schemes are effective at motivating communities to collect and organize recyclable waste. In addition, inspiring the public to organize recyclable waste reduces the burden for material recovery facilities to separate waste, which could lead to lower recycling prices that can compete with that of virgin materials.

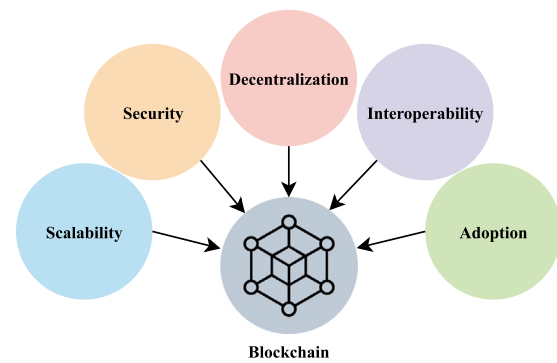


Fig. 15. Challenges that burden the wide adoption of blockchain.

7. Blockchain challenges

In this section, we will discuss the challenges in current blockchain networks (see Fig. 15). Specifically, we will focus on the trilemma of blockchains, i.e., scalability, security, and decentralization. We will also discuss the interoperability and adoption of blockchain networks.

7.1. Scalability

Scalability is one of the primary challenges of blockchain. It indicates how well the blockchain can manage high transaction throughput and future growth. Traditional blockchains have low transaction throughput. For example, the Bitcoin blockchain has a throughput of 7 transactions per second. In recent years, the demand for higher transaction throughput has grown as more and more applications are built on blockchain. Researchers and developers have made significant efforts to improve the scalability of blockchain by creating Layer 2 chains that connect to the Mainnet blockchains [144]. For example, with Layer 2 solutions, Ethereum has improved its transaction throughput up to 100,000 transactions per second from 14 transactions per second [145]. Moreover, Layer 2 solutions, which are built on top of Mainnet blockchains, will not compromise the decentralization or security of blockchains. The improved scalability with Layer 2 solutions paves the way to apply blockchain in throughout the life of a product. Higher throughput enables the creation of extensive blockchain networks that are necessary for industrial applications.

7.2. Security

While blockchain technology uses a tamper-proof ledger of transactions, there are some potential issues and vulnerabilities that can threaten its inherent security features. Below we provide four primary ways that fraudsters and hackers threaten blockchain networks [146–148]. We also provide potential solutions for those security issues.

- **Sybil attacks:** In Sybil attacks, malicious nodes generate and use many fake network nodes, which may flood and crash the blockchain networks. Developing better consensus algorithms may create hurdles for Sybil attacks.

- **Routing attacks:** Blockchain networks rely on real-time and massive amounts of data transfers. In routing attacks, hackers can intercept data when it is transmitted to internet service providers. In this way, hackers can get the user's confidential data without the user's knowledge and users cannot see the threat. Implementing secure routing protocols, applying encryption, and using strong passwords can mitigate possible routing attacks.

- **Phishing attacks:** The goal of phishing attacks is to steal the user's credentials by sending legitimate-looking emails to wallet key owners. With the attached fake hyperlinks in the emails, the user's credentials and sensitive information can be collected. This leads to the damages

for the user and blockchain networks. By installing malicious link detection software and improving security awareness, phishing attacks could be prevented.

- **Distributed Denial-of-Service (DDoS):** In DDoS attacks, malicious nodes can flood the blockchain networks with spam transactions, which prevents the legitimate transactions from being confirmed. The legitimate transactions will be forced to either stay in the mempool or pay high transaction fee to be processed. As a result, the blockchain's operations could be significantly slowed down [148]. Excluding potential spam transactions from blocks could mitigate DDoS attacks, but this process can be computationally expensive.

7.3. Decentralization

While blockchain is inherently distributed, it is not inherently decentralized. According to a study conducted by Trail of Bits and commissioned by the United States government's Defense Advanced Research Projects Agency (DARPA), blockchain is not as decentralized as assumed [149]. In the study, the Nakamoto coefficient is used to indicate the number of entities sufficient to attack the system. The lower the Nakamoto coefficient, the more centralized the system. The study reveals that Nakamoto coefficients for Proof-of-Work and popular Proof-of-Stake blockchains are relatively low. For example, the Nakamoto coefficients of Bitcoin, Ethereum, Solana, and Polygon are 4, 3, 19, and 2, respectively [149]. This implies that some blockchains are relatively centralized to some extent.

7.4. Interoperability

Blockchain interoperability refers to the ability of blockchain networks to communicate and interact with each other. Since different blockchains have their own consensus protocols with different security levels, tokens, and data types, it is difficult to interoperate and communicate with each other seamlessly. Cross-chain bridge, which enables blockchains to communicate with other blockchains, is one of the solutions to enhance the interoperability of blockchain networks [150]. With cross-chain bridge, developers and users could access alternative blockchain networks and use their token for applications and smart contracts built on other blockchains.

7.5. Adoption

Although blockchain technology has significant potential, it is still not widely adopted. On one hand, the technology is relatively new and many businesses have not seen the benefits using blockchain technology. On the other hand, organizations are still skeptical about its security, due to lacking regulations. In future, better incentive mechanisms and thorough regulations are expected to be created for improving the adoption of blockchains. In addition, education about blockchains can increase its use in the future.

8. Discussion and conclusion

An important observation from this work is that multiple of the challenges faced throughout the life of a product stem from the lack of reliable data. The need to utilize data to inform major decisions and power essential technologies requires such data to be accurate and reliable. However, it is difficult to determine the legitimacy of information because it is possible to forge or tamper data. Moreover, the ability to manipulate information threatens the reliability of data and causes many issues to multiple industries. As a result, industries constantly seek for methods that maintain data trustworthy. An attractive solution for addressing the data reliability problems is blockchain technology due to its immutability and decentralization properties. Furthermore, in this survey we observed how industries have taken advantage of blockchain's inherent properties to keep data secure and credible.

In addition, after conducting this survey, we identified a gap in blockchain related literature. This gap lies in the application of blockchain to materials design. To the best of our knowledge, the use of blockchain within materials design is still very new. The need for reliable and reproducible data in materials design lead a subset of researchers to develop frameworks that utilize blockchain to facilitate the reproducibility of experimental and computational studies or enhance the security in materials databases. However, more work on this area could enable the reproduction of diverse experiments and help create more unified materials databases. Including this subject in our survey expands blockchain literature and motivates researchers to explore blockchain's potential in this area.

Overall, this study investigates how blockchain can benefit the industries involved in the design, production, distribution, and disposal of products. In particular, we conducted a survey that explored the literature on blockchain applications to processes and technologies that are relevant to these industries. As a result, this work identified various challenges each of these sectors faces and blockchain-based solutions that can tackle these issues. Additionally, the advantages of utilizing blockchain-based solutions were pointed out. This information can help researchers and practitioners understand how blockchain can be implemented to improve various areas within product design, production, distribution, and disposal.

This study faces some limitations. Specifically, this survey focuses on a subset of processes and technologies relevant to the industries that handle product design, production, distribution, and disposal. Apart from the processes and technologies discussed in this paper, there are several other areas that can utilize blockchain. For instance, instrument calibration is an important topic to multiple industries that could use blockchain to protect the authenticity of calibration certificates. Another example is waste management. This area can use blockchain to enable the traceability of waste, like how blockchain is used in a supply chain. In the future, we would like to explore more processes that can take advantage of blockchain technology within the industries responsible for the design, production, distribution, and disposal of products.

CRediT authorship contribution statement

Diego Segura Ibarra: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Fan Li:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Jianjun Zhu:** Writing – review & editing, Writing – original draft, Conceptualization. **Jinyuan Chen:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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

No data was used for the research described in the article.

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