Benha Journal of Applied Sciences (BJAS) **print: ISSN 2356–9751**
Vol. (10) Issue (7) (2025), (9- 28) **online: ISSN 2356–976x**

http://bjas.bu.edu.eg
engineering sciences

Intellectual Property Protection For 3D Printing Products Using Blockchain Technology in the Field of Industrial Design

Asmaa.G.Elgez, **Nermeen.K.Elgedawy and Osama. A.Nada**
Industrial Design Dept., Faculty of Applied Arts, Benha University
E-mail: asmaa.elgazz@fapa.bu.edu.eg

Abstract
This research examines the application of blockchain technology as a mechanism to augment intellectual property (IP) protection for three-dimensional (3D) printed products within the domain of industrial design. The escalating accessibility and decentralized nature of 3D printing technologies have intensified concerns regarding the unauthorized replication and dissemination of design files, thereby posing a considerable risk to the IP rights of designers and manufacturers. This study explores the potential of blockchain's intrinsic attributes—immutability, transparency, and decentralized architecture— to create an auditable and safe framework for the administration and safeguarding of digital design assets. It investigates how blockchain-based solutions can provide verifiable provenance for 3D printable files, monitor their utilization and transfer, and automate licensing agreements through the implementation of smart contracts. Furthermore, the research analyzes the advantages of blockchain in deterring counterfeiting, streamlining the administration of IP rights, and fostering trust among designers, manufacturers, and consumers. By addressing the challenges of IP infringement within the context of 3D printing, this study contributes to the development of robust strategies for safeguarding innovation and promoting a secure ecosystem for the design and production of 3D-printed products. The findings aim to provide insights into the feasibility and efficacy of blockchain technology in redefining IP protection mechanisms within the evolving landscape of digital manufacturing.

Key words: Blockchain technology, 3D printing, Additive Manufacturing, Intellectual Property, Industrial Design

1. Introduction

In recent decades, the 3D printing (3DP) business has had significant growth characterized by an expanded market size, greater segmentation within the industry, and a shift in concentration towards midstream and downstream industries. The agile 3DP-enabled supply chain facilities assist companies in sustaining competitiveness and addressing rapidly evolving client needs in the contemporary business landscape. Nonetheless, it necessitates a more intimate interorganizational relationship characterized by continuous interaction and collaboration between producers and designers throughout the value chain. The problem of safeguarding intellectual property (IP) in the digital age is one of the main obstacles to collaboration and information sharing. The protracted process and challenges of authorizing, defending, and generating profit have long plagued the intellectual property sector. Digital data, like the 3DP design, is more challenging to use as proof of intellectual property rights because of its many characteristics, including its vast volume, real-time nature, heavy reliance on electronic devices, ease of loss and manipulation, and so forth. Evidence gathering and responsibility confirmation for the infringement of digital intellectual property rights are further complicated by the openness of the Internet and features of 3DP designs, such as the importance of co-creation, sharing, and co-ownership. As a result, innovators and creators are increasingly demanding that their digital products be adequately protected. The growth of dispersed 3DP manufacturing networks for well-known products has been hampered by the absence of an effective method to provide IP protection throughout the 3DP supply chain. 3DP has not yet reached its full economic potential, which can be partially attributed to a variety of IP-related issues.

Industry 4.0 was developed with the goal of modernizing and enhancing the sustainability of industrial and manufacturing processes. It is accomplished using cutting-edge technology like robotics, additive manufacturing, and the Internet of Things. Blockchain is one such technology that offers numerous advantages like transparency, decentralization, and security. The idea of blockchain technology, which powers the now-famous cryptocurrency Bitcoin, was initially put forth in 2008. Since then, there have been numerous advancements and modifications made to blockchain technology. In addition to digital currencies, blockchain has expanded into other sectors like healthcare, governance, supply chain, and entertainment. [1] The convergence of advanced manufacturing technologies and digital innovation has

reshaped the landscape of industrial design. Among these advancements, 3D printing, or additive manufacturing, has emerged as a transformative tool, enabling decentralized production, customization, and rapid prototyping. However, the protection of intellectual property (IP) is severely hampered by the digital nature of 3D printing. Digital design files, once created, can be easily replicated, modified, or distributed without the consent of the original designer, raising urgent concerns about copyright infringement, patent violations, and loss of commercial value. Traditional mechanisms of IP protection, including copyright, trademarks, and patents, struggle to keep pace with the speed and fluidity of digital fabrication. Legal enforcement is often reactive, jurisdictionally constrained, and prohibitively costly. In this context, blockchain technology offers a promising paradigm shift. As a decentralized, tamper-resistant ledger system, blockchain provides a method to authenticate, timestamp, and trace digital assets across their lifecycle, potentially revolutionizing how IP rights are established and enforced in industrial design. This research explores how blockchain can be integrated with 3D printing workflows to enhance IP protection for designers and manufacturers. Specifically, it investigates the mechanisms by which blockchain can provide immutable provenance, secure licensing, and transparent usage tracking of 3D printable files and end products, thereby reducing IP infringement and foster innovation.

2. Material and methods

A mixed-methods strategy is used in this study, integrating qualitative and quantitative techniques:

- **Literature Review**: Critical analysis of academic and industry literature on IP law, 3D printing, and blockchain applications.
- **Case Studies**: Examination of existing platforms (e.g., Ethereum-based projects) that implement blockchain for IP management in additive manufacturing.
- **Prototype Development Study**: Study Design and simulation of a blockchain-integrated IP protection model using smart contracts and decentralized file storage.
- **Expert Interviews**: Semi-structured interviews with designers, IP attorneys, and blockchain developers to assess practical implications.

3. Purpose of the study

This study focuses on the way blockchain technology can be used to improve the protection of intellectual property (IP) for three-dimensional (3D) printed products within the domain of industrial design. The study aims to address the challenges posed by the increasing accessibility and decentralized nature of 3D printing technologies, which have intensified concerns regarding the unauthorized replication and dissemination of design files, thereby posing a considerable risk to the IP rights of designers and manufacturers. Examining the viability and efficacy of applying blockchain technology to safeguard the intellectual property rights of 3D-printed goods in the field of industrial design is the main goal of this study. The study's objectives are to:

- Analyze current intellectual property vulnerabilities in the 3D printing lifecycle.
- Explore blockchain-based frameworks for secure file management and rights enforcement.
- Present models and solutions for integrating blockchain into prototyping processes and 3D printing applications in industrial design.
- Evaluate the model's ability to protect design rights from unauthorized copying or distribution.

4. 3D Printing Technology

Additive manufacturing, another name for three-dimensional printing, includes a wide variety of technological procedures, each predicated on distinct operational principles and tailored for specific applications. Several of these techniques are prominent, including Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM), commonly known as Fused Filament Fabrication (FFF). [2] Each of these techniques employs unique material deposition or consolidation mechanisms to fabricate three-dimensional objects directly from digital design files. These varied approaches present distinct advantages and limitations contingent upon the intended application. A thorough understanding of this technological diversity within 3D printing is crucial for a comprehensive analysis of the intellectual property considerations associated with the development of the underlying hardware. The dynamic interplay between these developing technologies and the regulatory frameworks controlling their development and application will greatly influence the course of additive manufacturing. **Overview of Prominent 3D Printing Technologies is provided below** [3]

4.1. Fused Filament Fabrication (FFF) / Fused Deposition Modeling (FDM)

One of the most used 3D printing technologies, especially in the consumer and educational sectors, is fused deposition modeling (FDM), often referred to as fused filament fabrication (FFF). [4] This technique builds the three-dimensional object by layering material according to the digital model by extruding thermoplastic filaments through a heated nozzle. Because of its affordability, ease of use, and ability to create working prototypes, FDM has become a well-liked option for small enterprises, educators, and hobbyists looking for quick iterations and observable results.

4.2. Stereolithography (SLA)

One of the earliest additive manufacturing techniques, stereolithography (SLA) is unique in that it uses ultraviolet (UV) laser irradiation to selectively photopolymerize liquid resin into solid layers. SLA is appropriate for applications requiring precise surface finishes and intricate geometries, such jewelry design and dental prosthesis, because this method makes it possible to fabricate items with great dimensional precision and intricate features.[5] In contrast to FDM, SLA technologies usually require longer fabrication periods and more expensive materials.

4.3. Selective Laser Sintering (SLS)

A powerful laser is used in the powder-bed fusion 3D printing process known as Selective Laser Sintering (SLS) to selectively fuse powdered materials—typically metal alloys or nylon—into solid structures. SLS is ideally suited for demanding industries like aerospace and automotive because it provides substantial advantages in producing functional parts with exceptional mechanical qualities and complex geometries. One of SLS's main advantages is that it doesn't require support structures, which makes it possible to produce complex designs that other additive manufacturing methods would find difficult or impossible to execute.

4.4. Additional Prominent Technologies for 3D Printing

Beyond the prominent techniques, the 3D printing landscape encompasses other noteworthy methodologies, including:

- **Digital Light Processing (DLP):** Like SLA, DLP selectively cures liquid rein using a digital light projector. However, because DLP cures an entire layer at once, it frequently provides faster build times.
- **Binder Jetting:** In this technique, layers of powdered material are selectively coated with a liquid binding agent, which is then solidified.
- **Material Jetting:** This technique involves carefully launching tiny droplets of photopolymer material onto a build platform, with UV light curing each layer instantly. Printing in multiple colors and materials is made possible by this technique.

With its distinct capabilities, each of these technologies advances the area of additive manufacturing, opening a wide range of applications from direct digital fabrication of end-use components to quick prototyping and tooling. [7] Furthermore, 3D printing is fundamentally challenging traditional supply chain paradigms. Because on-demand, point-of-use production eliminates the need for large-scale storage and transportation facilities, lead times can be shortened, and the environmental effect may be lessened. Small businesses and individual inventors can now create and manufacture products without the large capital expenditure usually required for traditional manufacturing procedures thanks to this dispersed production approach. [8] Figure 1, though not provided here, would typically illustrate the sequential stages involved in creating a tangible 3D-printed artifact from a digital CAD file.

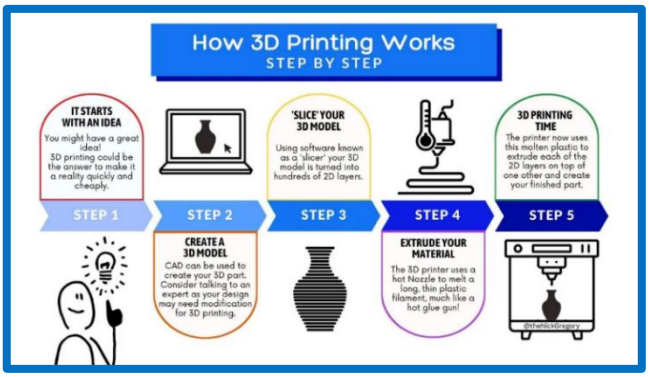

Fig. 1. shows the specific procedures needed to turn a digital CAD file into a product that can be 3D printed.[6]

5. Intellectual Property and Associated Challenges in Additive Manufacturing

The additive manufacturing (AM) process, inherently digital, necessitates the creation, iterative optimization, and validation of digital models prior to physical realization. This digital workflow generates sensitive processing and manufacturing data, forming a 'digital thread'– an information pathway encompassing data gathered and stored during the fabrication of a discrete

part. The digital nature of AM facilitates the unauthorized replication of product designs in small-scale production runs with greater ease compared to traditional analog manufacturing. Furthermore, the granular data exchange between manufacturers and clients inherent in AM, particularly in sectors such as medical 3D printing, necessitates a strong emphasis on confidentiality.

The increasing utilization of AM for consumer-oriented production and co-creation initiatives may involve the collection of customer data. AM technology promotes community involvement in the exchange of concepts and results within the context of "open innovation.". However, in the absence of clear regulatory frameworks, this collaborative environment can lead to legal disputes and violation of intellectual property (IP). The Internet's pervasiveness and the extensive use of information and communication technology (ICT) enable owners of printable content to readily upload digital design files, which can then be freely downloaded by individuals or companies. Subsequent modification and reproduction of downloaded content are easily achievable. As a result, newly printed products, including those that are shielded by copyrights, patents, or trademarks, quickly reach the market because they can be scanned and sold directly. Large firms frequently have the capacity to track down the source of illegal copies, while small and medium-sized businesses (SMEs) usually have a difficult time doing so. This problem is made more difficult by the widespread use of e-commerce, since it is challenging for IP owners to pinpoint the source of infringement when things that violate intellectual property are sold online.

The possibility of intellectual property infringement might hinder information sharing and cooperation in business-to-business (B2B) connections. The development of localized and decentralized AM manufacturing networks may potentially be impeded by the shortcomings of current IP protection procedures. A major enterprise information systems problem in the distributed development of printed parts is identifying "original," "copied," and "counterfeit" components or products that are crucial for safety-critical applications. In the digital age, AM supply chains face significant issues from data theft, infringement, and manipulation. The factors highlight how important it is to have strong IP protection in the AM environment. [9]

The operational processes of AM service providers exhibit variability. Despite the existence of diverse entities offering printing services, such as 3D printer distributors and dedicated 3D printing service providers, these are collectively referred to as '3D printing service providers.' Furthermore, a spectrum of customer types exists, ranging from companies to individuals, who may or may not possess design expertise. These customers are broadly categorized as '3D physical model consumers,' united by their need for physically printed items. Investigation reveals two primary business models for AM services: the self-developed model and the outsourcing model (as depicted in Figure (2). The self-developed model commences with requests from the 'consumer,' who may provide design ideas or external designs to the 'service provider.' Subsequently, the service provider's designer creates the necessary printing file, which is then used for fabrication. The physical item is ultimately delivered to the consumer. Interviewees generally perceive a low risk of IP infringement in this model. Nonetheless, there is a unique business model in which the original printing file is supplied by the customer. Regarding intellectual property rights, different businesses display different attitudes and actions. One typical strategy used by businesses that value intellectual property to handle possible infringement is to hire IP legal firms to confirm the IP source. This option is not applicable to all designs, though, and is usually restricted to those that have properly registered patents. Another tactic, which is mainly meant to safeguard the service provider, is for customers who contribute design files to sign an IP ownership statement. However, there are still very few businesses actively tackling IP-related issues. [9]

The advent and proliferation of 3D printing technology, characteristic of disruptive innovations, present notable challenges, particularly within the legal framework of intellectual property (IP). The democratization of manufacturing capabilities and the inherent ease of digital replication raise critical inquiries concerning ownership, copyright, and patent rights. Intellectual property laws are established to safeguard the entitlements of creators and innovators, granting them exclusive rights over their original works and inventions for a defined period. These legal instruments encompass various forms of protection, including copyrights, patents, and trademarks, each serving a distinct role in securing different categories of intellectual creations [10].

Copyright law protects original works of authorship, such as literary, musical, and artistic works, as well as software code and architectural designs. Copyright grants create

the exclusive prerogative to reproduce, distribute, and display their works, thereby preventing unauthorized exploitation by others. In the context of 3D printing, copyright concerns frequently arise in relation to the digital files and models that serve as the foundational blueprints for printed objects, posing questions regarding the legality of their reproduction as well as who owns the original designs.

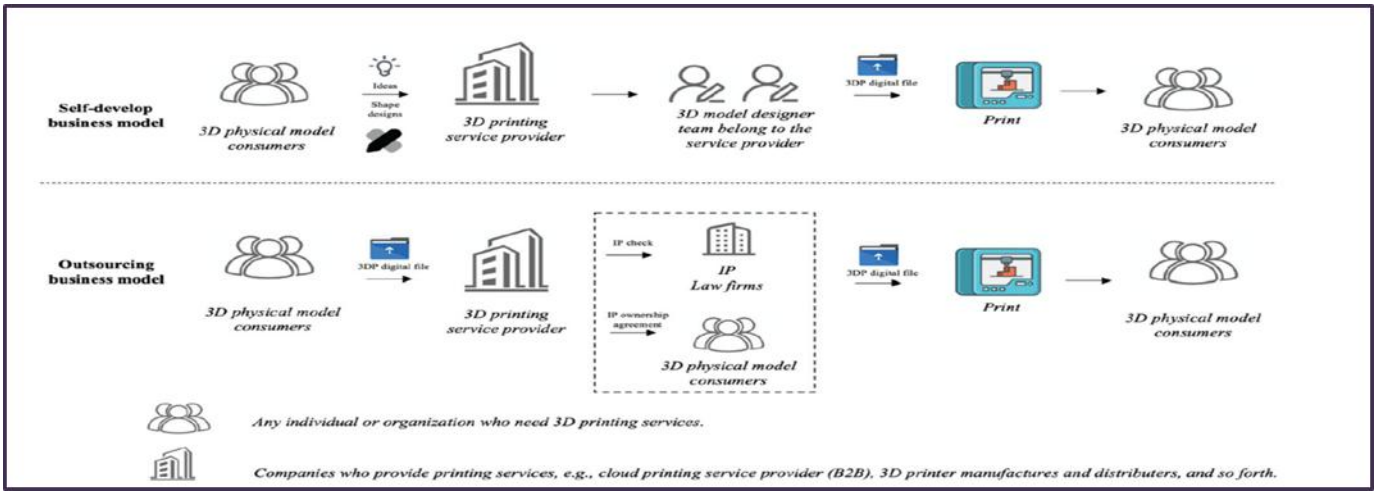

Fig. 2. 3D printing service operation process. [9]

On the other hand, patents provide exclusive rights to inventors for a certain period, usually 20 years from the date of filing, protecting discoveries and inventions. Patent protection can extend to a broad spectrum of innovations, including processes, machines, and compositions of matter. Within the 3D printing sector, patent-related challenges are particularly salient as manufacturers may inadvertently or intentionally infringe upon existing patents during the development of novel hardware or in the production of 3D-printed items that replicate patented designs [11,12]. Similarly, trademarks function to protect brand identity by preventing consumer confusion regarding the origin of goods or services. Trademarks can include logos, brand names, and slogans. Trademark concerns could arise in the context of 3D printing. when printed items incorporate recognizable logos or brand identifiers, potentially leading to claims of trademark infringement [13]. The recent advancements in 3D printing technology introduce unique complexities to IP law, as further elaborated in Table 1.

Table (1) Intellectual Property Considerations in 3D Printing

	IP Aspect	Challenge in 3D Printing
1	**Copyrights**	The intrinsic ease of digital design file duplication and dissemination presents a substantial risk of unauthorized reproduction of original creative works, thereby challenging established copyright protections.
2	**Patents**	The development of novel 3D printing hardware or the fabrication of objects that replicate patented designs through additive manufacturing processes carries a significant potential for patent infringement, necessitating careful consideration of existing intellectual property.
3	**Trademarks**	Incorporating identifiable logos or brand identifiers into 3D-printed items could be considered trademark infringement, necessitating caution to safeguard brand identity and stop illegal commercial exploitation.
4	**Democratization**	The increased accessibility of 3D printing technology empowers a wider demographic to engage in design creation and dissemination, consequently complicating the enforcement of existing intellectual property rights across a larger and more distributed user base.
5	**Global Distribution**	The digital format of design files facilitates their global exchange, introducing complexities for intellectual property enforcement due to inconsistencies and variations in national legal frameworks and regulatory regimes.
6	**Licensing Ambiguity**	Novel business models predicated on the sharing of digital designs raise fundamental questions regarding the applicability and effectiveness of traditional licensing agreements within this evolving technological and commercial landscape.

There are a lot of promises for creating stronger intellectual property (IP) frameworks specifically for 3D printing in a variety of sectors where additive manufacturing and digital design are becoming more and more common. Adaptive IP protections can be established by successfully tackling important IP issues, especially those pertaining to hardware innovation, digital file sharing, and the commercialization of printed works. These safeguards are especially important in industries like consumer goods, healthcare, and automotive, where 3D printing is transforming production processes, distribution systems, and product customization. Improved IP policies may guarantee legal compliance and promote innovation at the same time, creating a more secure and cooperative ecosystem for all parties involved in the 3D printing industry. [3]

A careful analysis of current legal frameworks is crucial in light of the dynamic relationship between technological innovation and intellectual property protection, especially as manufacturers and creators negotiate the challenges of defending their rights while promoting an innovative and collaborative culture. The commercialization of 3D-printed goods, the availability of downloadable digital design files, and a thorough examination of IP concerns pertaining to 3D printing gear will all be included in this investigation.

This research will examine three main themes through a thorough examination of the intellectual property issues raised by 3D printing technology. Each theme will clarify different but related aspects of intellectual property law in relation to additive manufacturing. Three main areas will be the focus: (1) intellectual property (IP) problems with 3D printing equipment, (2) copyright and licensing issues with downloadable 3D digital files, and (3) IP issues with commercially available 3D printed goods [3]. A sophisticated understanding of the related intellectual property issues is becoming more and more important as 3D printing technology develops. The intricate relationship between innovation and intellectual property protection calls for a careful analysis of current legal frameworks, especially as manufacturers and artists face the challenges of defending their rights while fostering an innovative and collaborative culture.

5.1. Intellectual Property Challenges in 3D Printing Hardware

The intricacies of patent protection are the focus of the many intellectual property issues that come with 3D printing hardware. For manufacturers, developers, and legal professionals working in the 3D printing space, a thorough grasp of these issues is essential as the sector develops and technological advancements multiply. The exact identification of important patented technologies integrated into 3D printers is a major component of these difficulties. Extrusion mechanisms in Fused Deposition Modeling (FDM) printers, laser systems used in Stereolithography (SLA) and Selective Laser Sintering (SLS) technologies, and software algorithms controlling the printing processes are just a few of the parts and procedures essential to 3D printing that have received patent grants. These patents cover a wider range of topics, including layer adhesion techniques and print quality improvement methods, in addition to technology implementations. Because manufacturers must carefully make sure that their innovations do not violate pre-existing intellectual property rights, the complex web of existing patents poses a significant obstacle to their efforts to build innovative 3D printing technology. [3].

The rise of a "prosumer" paradigm, in which customers utilize 3D printing to manufacture and consume items, further complicates this situation and raises hitherto unheard-of patent infringement issues. With 3D printing, anyone can create intricate things directly from digital files in home or local maker contexts, in contrast to traditional manufacturing models that are typified by centralized corporate management of production processes. Because they have to negotiate a huge and dispersed network of possible infringers, patent holders' ability to defend their rights is severely hampered by this decentralized arrangement. Furthermore, the ease with which digital designs may be shared and altered makes enforcement more challenging because there is a greater chance of both unintentional and deliberate violation [14].

In the field of 3D printing, cross-licensing also poses special difficulties, especially for sectors that depend on cooperative or interdependent designs. Traditional cross-licensing contracts usually assume clearly defined product boundaries and centralized production management, but 3D printing's intrinsic capacity to alter and personalize digital designs blurs these boundaries. Third-party users can modify designs to get around certain license requirements or combine components from several patents as digital files spread, creating derivative works that might inadvertently violate several patent rights. As a result, the implementation of cross-licensing agreements in the context of 3D printing requires the creation of

innovative frameworks that sufficiently take into consideration the adaptability of digital modifications and the likelihood of intricate, overlapping patent rights. [15]. Additionally, 3D printing democratizes production in ways that challenge the accepted conventions of cross-licensing and patent exhaustion. The shift to a "prosumer" market, in which customers create personalized goods for their own use, makes it more difficult to regulate licensing across the various networks that are involved in design sharing and replication. A decentralized and frequently global market of artists has become a challenge for traditional patent holders, who once depended on centralized manufacturers to enforce license agreements. This challenge calls for the creation of new cross-licensing models that can operate efficiently across digital platforms and protect patent rights in the face of the highly accessible and shareable nature of 3D files, particularly for industries with high customization rates like the medical or automotive sectors. [14]

5.2. Issues with Downloadable 3D Printing Files' Copyright and Patents

The basic digital representations of tangible objects meant for additive manufacturing are three-dimensional models, which are typically saved as Computer-Aided Design (CAD) files. These files can be regarded as intellectual property under copyright law since they are original authorships produced by designers, often involving substantial creative contribution. Such files are usually covered by copyright protection since they are categorized as "literary works" or "pictorial, graphic, and sculptural works" under legal frameworks, giving authors the only authority to duplicate, alter, and distribute their original works. [16] .However, the digital nature of 3D files introduces substantial challenges for copyright law, primarily due to their inherent ease of modification and dissemination across digital platforms, which complicates the effective enforcement of these exclusive rights. This intrinsic flexibility facilitates widespread circulation of diverse designs but concurrently raises pertinent questions regarding the practical efficacy of existing copyright laws in managing these digital assets.

The mass distribution of digital designs has been greatly facilitated by the emergence of online platforms like Thingiverse, MyMiniFactory, and Cults3D [17] that are devoted to the sharing of 3D-printable files. These platforms provide a huge and easily available collection of digital designs by allowing users to download, distribute, and, in certain cases, alter 3D models that other users have contributed. Although democratizing access to design tools and encouraging a creative community are two major advantages of these platforms, they also raise serious copyright issues. In this regard, users may unintentionally violate third-party intellectual property rights when they download or alter 3D models. A significant portion of the designs that are uploaded to these 3D model repositories are based on previously published copyrighted content, and both the original creators and end users run the risk of violating the rights of the original copyright holders if careful attributes are not included or if the original creators have not given their express consent. For example, popular characters or private designs may be included in publicly available 3D models, which could violate copyright, design patents, or trademark laws. Furthermore, it is unclear whether user modifications of preexisting designs constitute fair use or actionable infringement when there are no explicit legal standards addressing ownership rights in these adaptations. Once a digital file has been uploaded to a public platform or shared within private online communities, controlling its subsequent spread becomes a practically insurmountable task, highlighting the challenges of unauthorized copying, distribution, and digital piracy.

Licensing frameworks, such as Creative Commons (CC), have been developed to delineate the permissible parameters for the sharing, modification, and commercial utilization of 3D printable files. These licenses articulate a spectrum of usage rights, ranging from basic "Attribution" stipulations to "Non-Commercial" limitations, thereby allowing creators to maintain a degree of control over their intellectual property while simultaneously enabling access and derivative work creation by others. However, while certain Creative Commons licenses restrict commercial exploitation, the practical differentiation between personal and commercial use in the context of 3D printing can be indistinct. For instance, a user initially printing a file for personal purposes may subsequently decide to commercialize the resulting physical object, thereby introducing complexities in the enforcement of these licensing terms.

Copyright law traditionally grants creators exclusive rights over derivative works, defined as novel creative expressions derived from one or more pre-existing original works. Within the context of 3D printing, the alteration or remixing of existing digital files by users

raises critical questions concerning whether such modifications constitute derivative works that require explicit authorization from the original creator [18]. For instance, a user downloading a CAD file for a smartphone case and subsequently adding custom decorative designs technically involves the alteration of the original digital work. Determining whether such alterations exhibit sufficient substantiality and originality to qualify as a new copyrightable work under prevailing copyright law is often a complex and inherently ambiguous process.

5.3. Issues with Copyright and Patents in Commercially Available 3D Printed Products and Parts

The emergence of 3D printing technology and the subsequent Marketing of products made with 3D printing have introduced complex and rapidly evolving Intellectual property (IP) landscape considerations. The inherent capability of 3D printing to facilitate the rapid and decentralized replication of physical objects raises fundamental inquiries regarding design ownership, the legal scope of IP rights, and the allocation of liability in infringement cases.

A central challenge in the domain of 3D-printed items lies in the often-subtle distinction between genuinely original designs conceived by creators and objects that are mere reproductions of pre-existing designs. For instance, when a designer creates an original product or component, they automatically get copyright protection for that design, which gives them the sole authority to make copies and distribute their original work. However, because 3D printing technology is so revolutionary, it may be possible for anybody or anything with access to the digital design file to duplicate that item, which would be a clear violation of the original creator's legally protected copyright. When products are offered to the market for sale, it becomes crucial to distinguish between the original and copied things. Offering replicated items for sale without the explicit consent or permission of the original creator can lead to formal legal claims of copyright infringement. Furthermore, this scenario introduces complexities to the legal doctrine of fair use, as numerous users may modify or personalize existing designs. Such modifications raise intricate questions about whether these alterations are substantial enough to transform the design sufficiently to avoid a legal finding of infringement or whether they should be legally classified as derivative works, which may still necessitate the explicit authorization of the original creator [19].

In the context of products and components protected by patents, patent law constitutes another critical legal framework directly relevant when 3D-printed products are produced that effectively replicate existing patented products or components. In sectors characterized by a high degree of technological innovation, such as the automotive and aerospace sectors, where patented components often form the core of product design and overall functionality, 3D printing presents a unique and significant challenge to established intellectual property rights. A person or business may be held legally responsible for directly violating the patent holder's exclusive rights if they use 3D printing technology to duplicate a product or part covered by a valid patent without getting the required consent or license from the patent holder. In the field of 3D printing, patent infringement can happen if someone prints a product that successfully reproduces a patented design, whether it's a complex mechanical component, a replacement part for machinery, or a consumer-facing product. Since this kind of manufacture may get around the conventional processes of mass manufacturing and established distribution channels, this problem is most noticeable when such parts are made on demand or in small quantities for either individual use or commercial resale. Depending on the exact claims made in the patent documentation and whether the 3D-printed product in issue is within the legally defined parameters of the patented design or its functional elements, the precise extent of patent protection can vary significantly.[20]

Potential liability for patent or copyright infringement may be imposed on several parties participating in the complex production and distribution processes of a 3D-printed product when it is put up for commercial sale. Among these possibly accountable parties are: **(I) The 3D model's designer:** If a designer builds a digital 3D model of a patent- or copyright-protected object and then makes the model available for download or direct commercial use, they could be held legally responsible for infringement if the printed design they produce successfully copies the protected product without the owner of the IP rights' prior consent. **(ii) The Printed Item's Manufacturer:** If a manufacturer prints and then sells an item based on a 3D model, they could be held legally responsible if the final product is discovered to violate a legitimate patent or copyright. This liability is

especially likely to occur if the maker directly benefits from the design's illegal reproduction and sale or may be shown to have knowledge of its infringement.

(iii) The End User Who Prints and Sells the Object: End users who buy 3D-printed items and then sell them or modify and market them may also be held liable for intellectual property infringement. While some fair use clauses in copyright law may provide some protection for people who print things only for their own use, the act of commercializing 3D-printed goods greatly increases the legal concern involved. In cases of intellectual property infringement involving 3D-printed goods, the precise allocation of liability frequently depends on the particulars of the case, such as the degree of knowledge and the intent of each partner in the manufacturing and distribution chain.

Legal disputes in this intricate field usually focus on the extent of the manufacture and subsequent distribution of the infringing goods, as well as whether the infringement was intentional or merely unintentional. Legal disputes in this intricate field usually focus on the extent of the manufacture and subsequent distribution of the infringing goods, as well as whether the infringement was intentional or merely unintentional. [20]

Businesses that manufacture and market 3D-printed goods have to carefully manage the complex web of intellectual property rights, which may call for formal licensing agreements or royalties to be paid for the permitted use of patented or copyrighted ideas. This proactive strategy can assist in preventing expensive and drawn-out legal conflicts, such as those brought by IP rights holders who are requesting monetary damages for the unapproved use of their protected works. Additionally, a wide spectrum of people can now easily commercialize ideas thanks to the quick growth of digital platforms and online marketplaces where users can easily offer 3D-printed goods for sale. Because these online marketplaces are inherently global, it is very challenging to effectively enforce national IP laws and stop the unauthorized reproduction of copyrighted or patented designs, even though these platforms frequently incorporate certain mechanisms meant to help creators protect their intellectual property rights. With the growing availability of consumer-grade 3D printers, the cost and technical effort needed to replicate 3D objects have drastically decreased, exacerbating problems like the prevalence of counterfeit goods and the pervasive practice of design piracy in this digital age. [3].

The unapproved use of identifiable logos or other brand identifiers is a serious intellectual property issue that comes up in the marketing of 3D-printed goods. With the use of three-dimensional printing technology, tangible items that can contain registered trademarks can be produced, including consumer goods, fashion accessories, and even functional parts bearing business logos. For instance, a person or business may use the logo or trademark of a well-known brand while creating a 3D-printed product, such a personalized smartphone cover or a toy. Consumers may be misled into thinking that the 3D-printed product is officially endorsed or directly manufactured by the trademark holder if the brand's trademark is used without the owner's express consent. This could result in legal claims of trademark infringement. Because the production and subsequent distribution processes are decentralized, it can be especially difficult to protect trademark rights effectively in the context of 3D printing [21]. Although it isn't included here, Table 2 would normally list the main intellectual property issues—like copyright, patents, and trademarks—related to the selling of 3D-printed goods, as well as the difficulties these issues present and possible solutions.

Table (2) The primary Intellectual Property concerns associated with the sale of 3D-printed items

Aspect	Key Issues	Challenges	Potential Solutions
Copyright Infringement (Sale of Replicated Designs)	- Replication of original designs without creator's permission. - Sale of replicated items infringing on creator's exclusive rights. - Ambiguity of "fair use" in modified designs.	- Difficulty in distinguishing between original and replicated items. - Determining if modifications constitute infringement or derivative works. - Enforcing copyright in a decentralized production environment.	- Clear legal guidelines on the scope of copyright in digital 3D models. - Robust digital watermarking and tracking technologies. - Streamlined licensing mechanisms for 3D printable designs. - Educational resources for users on copyright law.
Patent Infringement (Sale of Patented Replicas)	- Unauthorized replication of patented products or parts. - Infringement occurs when a 3D-printed item replicates a patented design or functionality. - Production of demand and small-scale manufacturing bypassing traditional enforcement.	- Determining if a 3D-printed item falls within the scope of patent claims. - Identifying responsible parties for infringement (designer, manufacturer, end-user). - Adapting patent enforcement strategies to decentralized production.	- Clearer legal frameworks defining patent infringement in the context of 3D printing. - Development of technologies to track and identify patented designs in digital files. - Licensing models that accommodate on-demand and small-scale production.
Liability for Infringement	- Determining who is responsible for copyright or patent infringement in the production and sale process. - Liability can potentially fall on designers, manufacturers, or end-users. - Distinguishing between willful and accidental infringement.	- Complexity of supply chains involving digital design, printing, and sale. - Lack of clear legal precedents in 3D printing infringement cases. - Difficulty in tracing the origin and distribution of infringing items.	- Legal frameworks that clearly define the responsibilities of each party involved. - Mechanisms for verifying the IP status of 3D models before production and sale. - Insurance and indemnity provisions for manufacturers and sellers.
Commercialization Challenges	- Navigating IP rights, licensing agreements, and royalties for protected designs. - Risk of costly legal disputes for unauthorized use. - Difficulty in enforcing IP laws on global online marketplaces. - Prevalence of counterfeit goods and design piracy.	- The global and decentralized nature of online sales platforms. - Low cost and effort for unauthorized reproduction. - Lack of standardized international IP enforcement for 3D printed goods.	- International cooperation in IP enforcement for digital and physically printed goods. - Platform accountability for monitoring and removing infringing listings. - User education on the importance of respecting IP rights.
Trademark Infringement (Use of Logos and Brand Identifiers)	- Unauthorized inclusion of logos or brand identifiers in 3D-printed objects. - Potential confusion among consumers regarding\endorsement or manufacturing origin. - Dilution of brand distinctiveness and reputation.	- Difficulty in monitoring and controlling the use of trademarks in decentralized production. - Global reach of online platforms facilitating the sale of infringing items. - Lack of awareness among users regarding trademark law.	- Clear guidelines and restrictions on the use of trademarks in 3D-printed designs. - Platform monitoring and enforcement of trademark policies. - Legal repercussions for unauthorized commercial use of trademarks.

6. Emerging Solutions and Legal Frameworks at the Intersection of Intellectual Property and 3D Printing

The intersection of intellectual property (IP) law and 3D printing technology is a complex, diverse, and quickly changing problem. As 3D printing technologies maintain their continuous trajectory of advancement, existing legal frameworks are increasingly demonstrating limitations in adequately addressing the novel complexities arising from the paradigm shift towards digital fabrication and the unprecedented ease of replication.

6.1. Current Legal Landscape: Traditional IP Laws and Their Inherent Limitations in the Context of 3D Printing

Presently, copyright law, a fundamental pillar of IP protection, serves to safeguard the unique creative expression intrinsically embedded within digital 3D models, thereby granting original creators a comprehensive suite of exclusive legal rights. These rights include fundamental control over reproduction, public distribution, and the creation of derivative works through modification of their original creative expressions. Patent law, operating within a distinct sphere of IP protection, specifically applies to designs deemed novel, inventive, and industrially applicable. This legal framework is vital for controlling the 3D printing of products and elements that are already covered by legally binding patents. Trademark law, functioning within the domain of commercial identification, serves to protect distinctive logos, unique brand identifiers, and other recognizable marks actively utilized in trade and commerce. This legal domain is particularly relevant for effectively addressing critical issues such as the proliferation of counterfeit goods and the unauthorized commercial use of established brand names in the context of 3D-printed goods offered for sale to consumers. [22]

However, it is critically important to recognize that these foundational legal frameworks, while essential in their historical and ongoing application, were fundamentally conceived and meticulously developed for a world primarily defined using comparatively centralized manufacturing processes to produce and distribute tangible, physical things. The inherently decentralized and intrinsically digital nature of 3D printing technology presents a series of profound and multifaceted challenges to the effective and seamless application of these traditional legal constructs in several key and increasingly significant ways. For instance, while copyright laws do indeed extend a degree of legal protection to digital 3D models as original works of creative authorship, they do not specifically and adequately address the unprecedented ease and rapidity with which digital design files can be replicated, readily modified by end-users, and widely distributed across an array of interconnected digital platforms. Similarly, patent laws are traditionally predicated upon the tangible and physical act of producing concrete objects, which introduces a significant layer of complexity when attempting to directly apply their principles and enforcement mechanisms to the fundamentally digital realm of 3D models that are initially created and subsequently undergo various modifications within the digital space before any physical items are actually brought into existence through the printing process [23]. Current patent regulations, largely formulated in an era of centralized mass production, do not fully and adequately account for the widespread ability of individual users to produce patented items on an on-demand basis, particularly when such production occurs in small quantities or is intended solely for personal, non-commercial use.

Since digital design files can now be distributed instantly and seamlessly throughout the world thanks to 3D printing technology, the effective enforcement of IP rights across international borders has become an increasingly arduous and complex task. The intrinsically digital character of 3D models adds even more complication to this already difficult environment, making the crucial question of legal jurisdiction even more difficult to resolve. It is extremely difficult, if not impossible, for IP rights holders to successfully pursue legal action in cases of infringement because a digital 3D model that is first uploaded to a server in one country can be easily downloaded and then printed in another independent sovereign nation. Although the World Intellectual Property Organization (WIPO) has made admirable first steps toward fostering international cooperation on several intellectual property law-related topics, more coordinated and global efforts are necessary to develop a coherent and broadly applicable global legal framework that is especially suited to the particular and quickly changing challenges presented by the transformative technology of 3D printing. [24]

6.2. Emerging Technological, Legislative, and Collaborative Solutions to Address the IP Challenges of 3D Printing

As the multifaceted challenges surrounding the intricate intersection of 3D printing technology and intellectual

property (IP) rights continue to evolve rapidly, a diverse array of innovative technological advancements, proactive legislative initiatives, and collaborative industry-driven frameworks are emerging as potential and increasingly viable pathways to effectively address these complex and pressing issues. One promising technological innovation is the increasing and strategic utilization of blockchain technology as a robust and decentralized mechanism to securely track, transparently verify, and efficiently manage the growing volume of digital 3D designs [25]. Concurrently with these technological advancements, legislative bodies in various jurisdictions are increasingly acknowledging that to effectively handle the difficulties presented by 3D printing technology, established intellectual property rules urgently need to be updated in a thorough and timely manner. To better account for the global nature of 3D printing and the widespread digital distribution of design files, these efforts are being supported by emerging international collaborations, such as those launched by the World Intellectual Property Organization (WIPO), which aims to achieve greater harmonization of often disparate intellectual property laws across national jurisdictions. The proactive creation of collaborative intellectual property frameworks within industrial sectors, like the fashion or automotive industries, to strategically create industry-led standards and best practices for the robust protection of 3D-printed designs is another increasingly popular and potentially successful emerging solution. [9]. In addition to encouraging ongoing innovation and crucial cooperation, industry stakeholders can jointly develop standards that successfully defend the legal interests of downstream manufacturers and original designers. For instance, major corporations in the automotive industry could work together to develop a single, transparent framework for the safe licensing and sale of 3D-printed replacement parts, greatly lowering the risk of intellectual property infringement while guaranteeing that customers have access to reasonably priced and easily accessible parts. [26]

7. Blockchain Technology

Blockchain, a distributed digital ledger technology, has become a major invention in recent years and has the potential to revolutionize several industrial settings. In 1991, the fundamental idea of blockchain was first put forth as a research project. Two decades later, in 2008, its first real-world use came to pass when Satoshi Nakamoto created the cryptocurrency Bitcoin, a peer-to-peer, trustless network for electronic transactions that uses a proof-of-work consensus method. [27]. Bitcoin is a peer-to-peer electronic currency system that was first introduced by Satoshi Nakamoto in 2008. Bitcoin was an innovative digital money that eliminated the need for conventional financial middlemen. By using a peer-to-peer network architecture in which every transaction was documented on a distributed ledger, the problem of double-spending was resolved. Only after being verified by a consensus of the network's nodes were transactions added to this ledger. Blockchain technology originated from this idea of a digital, peer-to-peer distributed ledger.
Blockchain technology gained significant global attention due to its inherent characteristics of immutability, decentralization, and democratic governance. It provides a system for secure and decentralized transactions by distributing data across a network in a unique and cryptographically secured manner. Blockchain has witnessed substantial adoption across both the financial and non-financial sectors, proving to be a revolutionary force in the field of information technology. Its implementation spans diverse sectors, including healthcare, supply chain management, and finance. Every node in a blockchain keeps a copy of the ledger, which is updated now of creation and linked to a timestamp. This makes it computationally impossible to change the data to any particular block later on. In general, there are three main types of blockchain architecture: public, private, and consortium (or federated). Public blockchains offer open access for reading, writing, and verifying transactions, exhibiting full distribution and decentralization. In contrast, private blockchains grant write access to a single entity or organization, typically lacking significant decentralization characteristics. Federated blockchains, however, are governed by multiple organizations or representatives who collectively make decisions for the benefit of the network [1].

The blockchain is a publicly distributed ledger that can effectively, verifiably, and permanently record transactions between various participants across many nodes globally at the same time. Because of its immutable record-keeping, minimal downtime vulnerability, and resistance to censorship and data falsification, previous research suggests that blockchain technology has significant promise for enabling data transformation and secure exchange inside supply chains (Nakamoto, 2008). Blockchains offer significant potential

in addressing the challenges of tracking and authenticating 3DP design information [9].

8. Protection of 3D Printing Products Utilizing Blockchain Technology

In response to the challenges of unauthorized copying, distribution, and digital piracy, various technological solutions have been proposed and are under development to effectively address these multifaceted issues. These consist of various digital tracking tools, digital watermarking methods, and Digital Rights Management (DRM) systems. [28]. By immediately inserting identifying information into a digital file, digital watermarking allows designers to potentially track their creations even if they are later shared or altered. Digital Rights Management (DRM) systems can be used to regulate how digital files are used, shared, or printed, but because of the restrictions they place on how users can interact with legally obtained digital information, this technology has frequently been criticized and controversial. Furthermore, by offering a decentralized and unchangeable record of a file's ownership history and related usage rights, blockchain technology has become a potential option for controlling ownership rights in digital assets. When creators' digital designs are copied or used by others, this decentralized ledger system may guarantee that they receive fair pay. Although these technological advancements present encouraging methods for safeguarding 3D printable files, user acceptance, the need for strict regulatory monitoring, and the development of strong enforcement mechanisms remain obstacles to their widespread adoption. [29]

Innovative technologies like blockchain and Digital Rights Management (DRM) systems have been proposed and are increasingly being investigated as promising and potentially transformative solutions in direct response to the new and complicated challenges in effectively protecting intellectual property rights for digital 3D designs and physically printed objects. The enormous potential of blockchain technology to efficiently manage copyrights and usage rights in the digital 3D printing industry has already been shown by several innovative pilot projects and perceptive real-world case studies. For instance, by strategically utilizing the inherent security, transparency, and immutability of blockchain technology, the Arcadia Group's ground-breaking 3D Print Blockchain Platform actively tracks the ownership and precisely defined licensing terms connected with 3D printing designs. This platform guarantees that original creators maintain a high level of control over their priceless designs and obtain just compensation for each authorized use or modification of their intellectual property by directly embedding distinctive digital signatures and thorough metadata into digital 3D files. [30]. Similarly, Mattereum, a sophisticated blockchain-based platform, establishes a direct and verifiable connection between digital 3D models and the corresponding physical products created from them, thereby ensuring enhanced transparency in both ownership and clearly defined usage rights throughout the design lifecycle [31]. While blockchain technology offers robust security and unparalleled transparency in managing digital assets, the overall cost-effectiveness of implementing such sophisticated solutions, particularly for smaller-scale producers and independent designers with limited financial resources, remains an important area of ongoing evaluation and optimization. However, successful and operational platforms like MyMiniFactory, which actively utilize blockchain technology for the enhanced protection of digital designs shared on their platform, demonstrate that the long-term benefits—such as a significant reduction in costly legal disputes arising from infringement and the efficient management of royalty payments to creators—can potentially outweigh the initial investment costs associated with the implementation and maintenance of such systems [32] [33]. A comprehensive and rigorous cost-benefit analysis in this evolving context strongly suggests that the inherent transparency, robust security, and automated tracking capabilities provided by blockchain technology have the significant potential to substantially reduce the long-term financial burdens and operational complexities traditionally associated with intellectual property infringement and the unauthorized use of digital designs.

The potential of blockchain technology has been explored across diverse industries. At its core, a blockchain is an innovative approach to decentralized data management that serves as a publicly available distributed ledger that guarantees the integrity of different kinds of transactions. Every transaction is timestamped historically and is contained within a cryptographically secured block that is linearly sequenced, with each new block including data from all blocks that came before it. The implementation of blockchain technology establishes a decentralized network, fostering trust between participating entities without the necessity of a central intermediary.

Furthermore, the distributed shared ledger inherently replicates its content across numerous nodes. Provided that most ledger copies remain uncorrupted and unmanipulated, the accuracy of transactions or information can be reliably ensured, thereby shifting trust towards the redundancy provided by multiple copies. As a result, the trust built between diverse parties is supported by the immutability of data and the processes through which information is created, organized, and disseminated. To promote an innate level of trust, blockchains provide inherent benefits such as record immutability, improved security, digital information authenticity, data ownership control, and transaction transparency. These days, using blockchain technology into Additive Manufacturing (AM) procedures could result in more dependable, secure, and efficient workflows. A strong backend security layer that carefully logs and validates every action during the AM lifetime can be provided by blockchain. Given the increasing adoption of 3D printing across critical sectors such as the military, healthcare, and government, addressing associated security risks is paramount [1]. Therefore, it is essential to comprehend how blockchains might be strategically used to safeguard intellectual property in the 3DP sector, a field that is becoming more complex in the digital age. First, the 3DP supply chain may be vulnerable to data leaks due to the production and sharing of digital files, including CAD files. As a result, blockchains' unchangeable record-keeping features provide a workable way to protect the privacy of 3DP designs and reduce risk. Like this, Klöckner [34] proposed that by maintaining distributed copies inside the blockchain, encouraging information symmetry, and improving supply chain visibility, blockchains can lessen the IP and data security challenges related to 3DP [35]. Digital Rights Management (DRM) systems and blockchains are important enabling technologies for the development of 3DP methodology. They also play a major role in the commercialization of 3DP and the prevention of intellectual property theft in the 3DP supply chain. [3]

In this rapidly evolving context, a particularly promising and technologically sophisticated solution involves the innovative and strategic utilization of blockchain technology for the secure verification and transparent tracking of digital 3D designs. Blockchain's inherently decentralized and cryptographically secured ledger system possesses the significant potential to establish a tamper-proof, immutable, and transparent record of ownership and precisely defined usage rights for digital 3D files [34]. In addition to enabling original creators to efficiently register their distinctive designs and preserve unquestionable, auditable evidence of their original ownership, this technological capability would guarantee that any later uses or modifications of their priceless designs are appropriately attributed and possibly compensated in accordance with established licensing agreements. Furthermore, blockchain technology could play a crucial and increasingly important role in facilitating the efficient enforcement of licensing agreements and meticulously tracking the distribution of 3D models across interconnected digital networks, thereby providing a more effective and robust technological mechanism to combat the pervasive and economically damaging issues of digital piracy and unauthorized reproduction. While these new and quickly developing technologies are important and vital advancements in protecting digital 3D content, their widespread and successful adoption requires a careful and nuanced balancing act to prevent unduly limiting necessary collaboration within the design and manufacturing ecosystems, legitimate innovation, and end users' fundamental rights. The inherently decentralized and cryptographically secured nature of blockchain technology provides a tamper-proof and transparent digital ledger that meticulously records essential ownership details and precisely defined usage rights associated with digital assets, offering a potentially revolutionary solution for ensuring accurate and permanent attribution of intellectual contributions and fair compensation for authorized utilization of creative works. Through the direct integration of distinct digital signatures and extensive metadata into digital 3D model files, blockchain technology may enable designers to efficiently safeguard their priceless intellectual property against unapproved duplication, extensive digital dissemination, and unlawful commercial exploitation. Furthermore, this innovative and technologically sophisticated approach could significantly streamline the often-cumbersome enforcement of licensing terms, as blockchain systems possess the inherent capability to automatically control access to digital assets and manage predefined usage rights, thereby offering enhanced and more robust protection against pervasive digital piracy. Digital data entry is necessary for a blockchain-based network. In contrast to other blockchain applications (such as the global trade network of Maersk and IBM, diamond

tracing, and food traceability), design files and manufacturing process data—two of the most important input data in the 3D printing ecosystem—are already digitally wrapped. Due to its pre-existing digital data infrastructure, 3D printing makes blockchain adoption easier than more traditional production methods because it is intrinsically dependent on a digital process chain. In essence, since many parts of the 3D printing process chain are already in digital format, they do not require digitization. Therefore, it is both viable and practicable to integrate a digital ledger with the 3D printing process [36]. Original equipment manufacturers (OEMs), designers, copyright holders, printing service providers, and maintenance operators in need of printed spare parts are all involved in the 3D printing environment. It's not always the case that these stakeholders trust one another. Contractual agreements are possible, but they need safeguards to ensure safe and efficient corporate operations. Blockchain offers a workable answer in a situation where there are many interacting parties that require peer-to-peer communication. Greater independence, customization, organizational and geographic redistribution, localization, or interactivity of design and manufacturing processes are made possible by the digital encapsulation of product design and production process data, but the insufficiency of current IP and data security structures prevents 3D printing from taking advantage of these business model opportunities. [37]

By creating a 3DP digital model sovereign information storage system based on a blockchain architecture and available to end users via a digital platform, blockchain technology can technically support the safe environment required for distributed 3D printing business models. This infrastructure enables 3D digital design resource transaction services and offers a complete chain for storing and retrieving the intellectual property data of digital designs [36]. The basic idea is to map onto the blockchain the lifecycle of a 3D-printed item (shown in Figure 3), including all relevant stakeholders and their associated workflows. These stakeholders include end users, original equipment manufacturers (OEMs), logistics service providers, suppliers of materials, and providers of 3D printing services. Other complementary actors that mainly deal with the information flow, in addition to these entities involved in the physical flow of parts, could include external originators who upload their designs to platforms, regulatory bodies, certification bodies, and financial institutions (for payments, financing, or insurance). Component-related data, such as printing licenses, production process data, material provenance, test and simulation data, payment records, and component certifications, are protected and shared by the blockchain when this data is fed into a secure blockchain platform. The platform, designers, 3DP manufacturers, and legal authorities work together to create an alliance blockchain, creating an ecosystem where parties may reliably and transparently communicate and trace information. [38]

This infrastructure can be used to create other services, like 3D digital design trading platforms. To support the complete business process, the blockchain-enabled platform architecture will consist of five layers: the application and display layer, the contract layer, the consensus layer, the network (business) layer, and the data storage layer [39] [40]. Figure 4 shows the platform structure and architecture's original design.

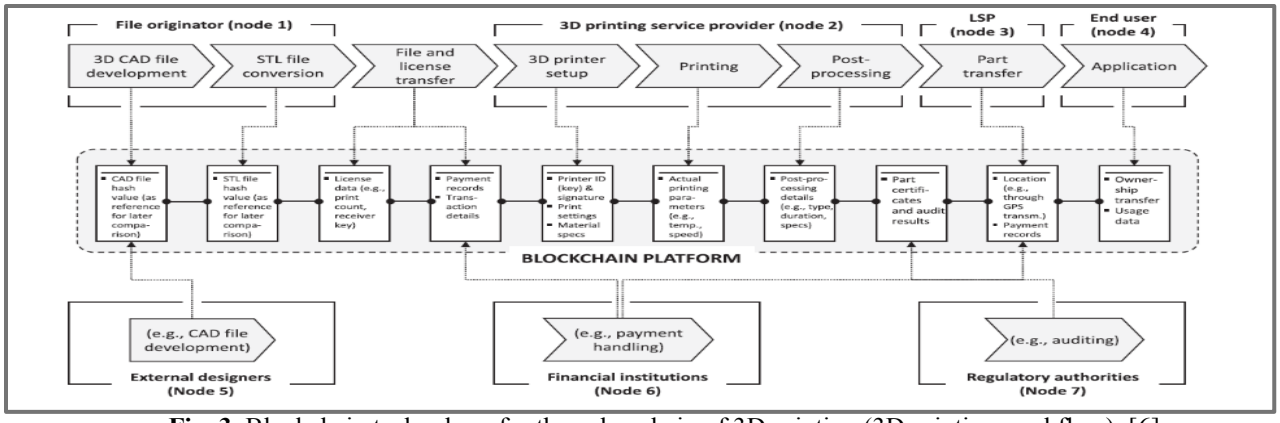

Fig. 3. Blockchain technology for the value chain of 3D printing (3D printing workflow). [6]

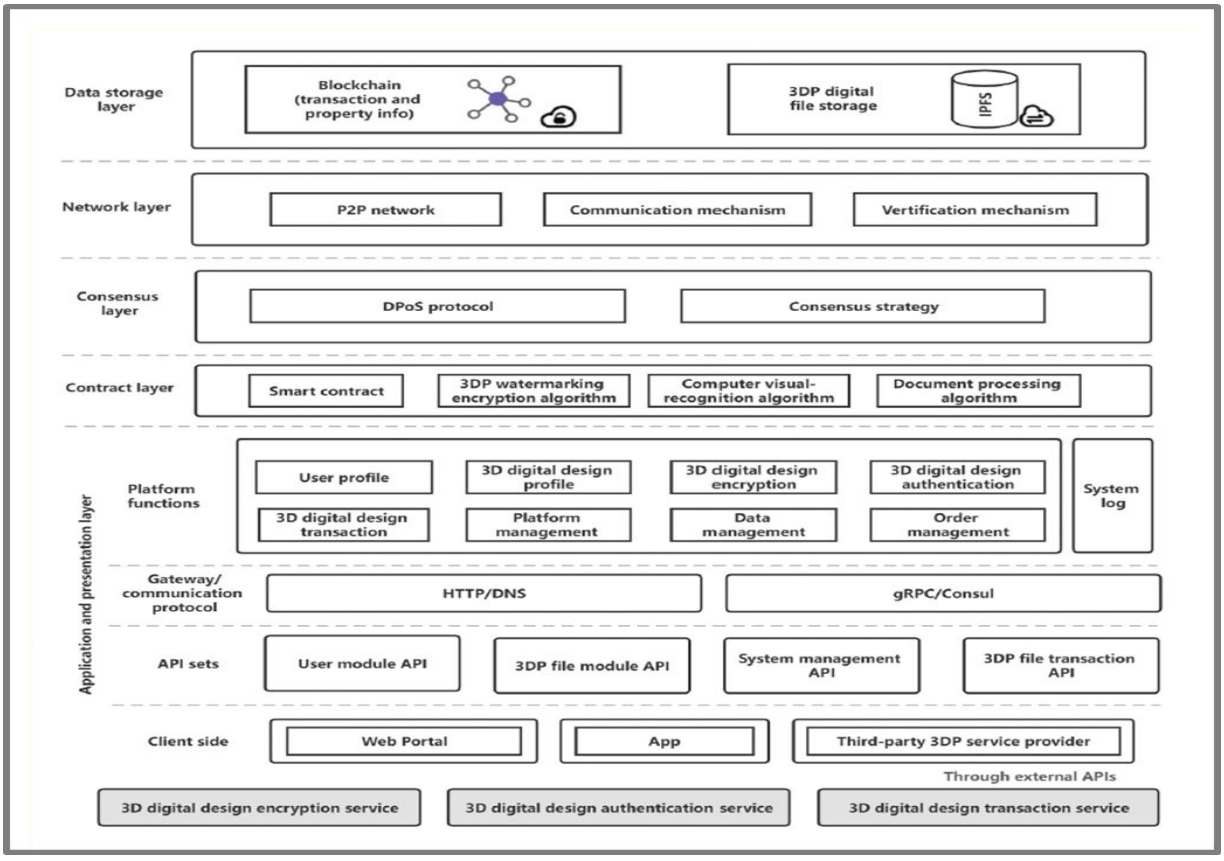

Fig. 4. The platform architecture supported by Blockchain

9. Challenges and Limitations

Obstacles to Blockchain Adoption in the 3D Printing Industry. The integration of blockchain technology as an effective solution for the 3D printing industry faces multifaceted obstacles spanning technical, economic, and legal domains. Scalability and performance limitations are primary concerns, as current blockchain architectures struggle to process the high volume and velocity of data generated by complex 3D printing workflows, potentially leading to unacceptable latency and high transaction costs. The storage of large 3D model files directly on-chain is impractical, necessitating off-chain storage solutions that introduce new integrity management challenges. Furthermore, interoperability issues arise from the diverse range of hardware, software, and materials in the industry, compounded by varying blockchain protocols, making seamless integration difficult. The energy consumption of certain blockchain consensus mechanisms, particularly Proof-of-Work, also presents an environmental and financial hurdle, deterring sustainability-focused organizations.

Economically, the high initial investment and ongoing operational and maintenance costs of implementing blockchain solutions can be prohibitive, especially for small and medium-sized enterprises. This is exacerbated by a significant shortage of skilled professionals proficient in both blockchain and additive manufacturing, driving up development and management expenses.

From a regulatory and legal standpoint, ambiguity regarding the legal status of blockchain records in intellectual property (IP) disputes is a major impediment. Many jurisdictions do not yet clearly recognize blockchain-registered digital assets as conclusive evidence of ownership or provenance, undermining its utility as a trusted IP enforcement tool. This is compounded by data privacy and transparency conflicts, where blockchain's inherent immutability and transparency can clash with regulations like GDPR's "right to be forgotten," creating a tension between IP

protection and regulatory compliance. Moreover, blockchain's enforcement limitations mean that while it can record infringement, actual IP rights enforcement still relies on traditional legal action, placing the burden of pursuing remedies on rights holders.

Finally, significant adoption and ecosystem challenges persist. The technological complexity and usability of blockchain systems, requiring a steep learning curve for cryptographic keys, wallets, and smart contracts, deter designers and manufacturers lacking technical expertise. This leads to low awareness and industry adoption, as skepticism about blockchain's practicality and the inertia of established workflows contribute to slow integration rates. The absence of standardized governance mechanisms and clear return on investment (ROI) from practical use cases further hinders broad stakeholder support, preventing the formation of a cohesive, industry-wide blockchain ecosystem for 3D printing.

10. Results and discussion

The research findings demonstrate the significant potential of blockchain technology to revolutionize intellectual property (IP) protection within the realm of 3D printing. The inherent characteristics of blockchain, including its immutability, transparency, and decentralized structure, offer a robust framework for establishing secure and auditable records of digital design assets. The implementation of blockchain-based solutions enables the creation of a tamper-proof ledger that meticulously documents the provenance of 3D printable files, tracing their origin, modifications, and transfers with unparalleled accuracy. This capability effectively addresses the pervasive issue of unauthorized replication and distribution of digital designs, providing designers and manufacturers with a powerful tool to safeguard their IP rights. Furthermore, the research highlights the efficacy of blockchain in automating licensing agreements and facilitating secure transactions within the 3D printing ecosystem. To streamline the licensing process and guarantee equitable compensation for creators, smart contracts—self-executing agreements encoded on the blockchain—can automate the terms of use, royalties, and access control for 3D design files. By reducing the possibility of data manipulation and single points of failure, blockchain's decentralized architecture improves the security and robustness of the IP protection system.

11. Recommendations

Considering the study's conclusions, it is advised that stakeholders across the 3D printing industry actively pursue the adoption and integration of blockchain technology to strengthen IP protection mechanisms. This includes fostering collaboration between designers, manufacturers, technology developers, legal experts, and regulatory bodies to establish standardized protocols and best practices for blockchain implementation. Creating user-friendly platforms and tools that make it easier to register, manage, and license 3D design files on the blockchain is essential to achieving the full benefits of blockchain technology. Furthermore, educational initiatives should be undertaken to raise awareness among designers and manufacturers about the capabilities of blockchain and its potential to enhance their IP rights. Continued research and development are essential to address any scalability, interoperability, and regulatory challenges associated with the widespread adoption of blockchain in the 3D printing sector. To develop more complete and effective IP management systems, future research should investigate how blockchain might be integrated with other cutting-edge technologies like cloud computing and artificial intelligence.

12. Conclusions

Additive Manufacturing (AM) can leverage blockchain technology at the transaction node level to ensure comprehensive traceability of all assets, establish verifiable origin, and provide users with a complete lifecycle view of each component. Blockchain offers authentication by detecting file corruption or unauthorized conversion. However, strong supply chain data protection is required for successful adoption in all stages of the AM digital supply chain. The final part structure and its related engineering data must be regarded as high-value assets needing strict protection, starting with the design stage. File encryption, smart contracts and digital licensing, and the development of digital trust made possible by blockchain use can all be used to secure sales transactions. Component designers can prevent unwanted access until the files are processed by AM-selected machines by encrypting design files, which guarantees that only authorized people can view the supplied information. The intellectual property owner can then establish data access permissions, duration, and acceptable usage conditions for component manufacture using a smart contract, which serves as a licensing mechanism. Designers transmit encrypted design files, along with the corresponding digital license, to authorized entities within the supply chain via secure channels such as encrypted email, offline programs, or direct server access through secure application programming interfaces, depending on the required security level. Upon the creation of a physical component, it needs to be noted on a blockchain ledger and identified by a special digital reference**. Table 3** outlines specific challenges within AM that can be effectively addressed through the application of blockchain technology.

Table (3) problems in AM can be overcome with Blockchain.

	AM procedure	Problem/Needs	Blockchain requirements	Observations
1	- CAD Modelling	- Copyright issues/Unintended Design Modification	High	The decentralized architecture inherent in blockchain technology mitigates the risks of unauthorized alterations to design dimensions and the theft of design assets.
2	- Conversion to.STL	- Manipulation of layer thickness, element size	High	Enhanced security protocols within blockchain frameworks prevent any modifications to data without the explicit consensus and approval of all network participants.
3	- G-Code Generation	- G-Code manipulation	Moderate	Blockchain-enhanced security stops such modifications without all members' consent.
4	- Assembly of Components	- Copyright issues/Copyright issues/ Unintended Design Modification	Moderate	The permissioned nature of blockchain systems enables granular control over data accessibility, allowing specific components of an assembly to be restricted to authorized team members only.
5	- Digital Transfer of Designs	- Intellectual Property Theft/ Manipulation	Very High	The cryptographic security features of blockchain technology effectively prevent unauthorized access to data during online transfer, thereby enhancing data integrity and confidentiality against cyber threats.

References

[1] T. Ghimire, A. Joshi, S. Sen, C. Kapruan, U. Chadha, and S. K. Selvaraj, "Blockchain in additive manufacturing processes: Recent trends & its future possibilities," in *Materials Today: Proceedings*, Elsevier Ltd, 2021, pp. 2170–2180. Doi: 10.1016/j.matpr.2021.09.444.

[2] A. Kantaros, F. I. T. Petrescu, K. Brachos, T. Ganetsos, and N. Petrescu, "Evaluating Benchtop Additive Manufacturing Processes Considering Latest Enhancements in Operational Factors," *Processes*, vol. 12, no. 11, p. 2334, Oct. 2024, Doi: 10.3390/pr12112334.

[3] A. Kantaros, "Intellectual Property Challenges in the Age of 3D Printing: Navigating the Digital Copycat Dilemma," *Applied Sciences (Switzerland)*, vol. 14, no. 23, Dec. 2024, Doi: 10.3390/app142311448.

[4] J. Giannatsis, A. Vassilakos, and V. Dedoussis, "A Heterogeneous Infill Technique for Fused Deposition Modeling," *Procedia Manuf*, vol. 51, pp. 642–648, 2020, Doi: 10.1016/j.promfg.2020.10.090.

[5] M. Pagac *et al.*, "A Review of Vat Photopolymerization Technology: Materials, Applications, Challenges, and Future Trends of 3D Printing," *Polymers (Basel)*, vol. 13, no. 4, p. 598, Feb. 2021, Doi: 10.3390/polym13040598.

[6] "Im working on a poster that's going above the Printers in the Innovation Centre at my work, Do you think this explains the process well enough? : r/3Dprinting." Accessed: Apr. 21, 2025. [Online]. Available: https://www.reddit.com/r/3Dprinting/comments/14wp75y/im_working_on_a_poster_thats_going_above_the/?rdt=44419

[7] A. Kantaros *et al.*, "3D printing: Making an innovative technology widely accessible through makerspaces and outsourced services," *Mater Today Proc*, vol. 49, pp. 2712–2723, 2022, Doi: 10.1016/j.matpr.2021.09.074.

[8] E. Petersen and J. Pearce, "Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers," *Technologies (Basel)*, vol. 5, no. 1, p. 7, Feb. 2017, Doi: 10.3390/technologies5010007.

[9] H. K. Chan, M. Guo, F. Zeng, Y. Chen, T. Xiao, and J. Griffin, "Blockchain-enabled authentication platform for the protection of 3D printing intellectual property: a conceptual framework study," *Enterp Inf Syst*, vol. 17, no. 11, 2023, Doi: 10.1080/17517575.2023.2180776.

[10] A. Kulkarni and J. Pearce, "Patent Parasites: Non-Inventors Patenting Existing Open-Source Inventions in the 3-D Printing Technology Space," *Inventions*, vol. 8, no. 6, p. 141, Nov. 2023, Doi: 10.3390/inventions8060141.

[11] S. Bechtold, "3D Printing, Intellectual Property and Innovation Policy," *IIC - International Review of Intellectual Property and Competition Law*, vol. 47, no. 5, pp. 517–536, Aug. 2016, Doi: 10.1007/s40319-016-0487-4.

[12] J.-T. Hwang, B.-K. Kim, and E.-S. Jeong, "Patent Value and Survival of Patents," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 7, no. 2, p. 119, Jun. 2021, Doi: 10.3390/joitmc7020119.

[13] "View of The Intersection of 3D Printing and Trademark Law." Accessed: Apr. 21, 2025. [Online]. Available: https://www.jipitec.eu/jipitec/article/view/231/226

[14] W. Bai *et al.*, "Academic Insights and Perspectives in 3D Printing: A Bibliometric Review," *Applied Sciences*, vol. 11, no. 18, p. 8298, Sep. 2021, Doi: 10.3390/app11188298.

[15] S. Bechtold, "3D Printing, Intellectual Property and Innovation Policy," *IIC - International Review of Intellectual Property and Competition Law*, vol. 47, no. 5, pp. 517–536, Aug. 2016, Doi: 10.1007/s40319-016-0487-4.

[16] "Copyright Law of the United States | U.S. Copyright Office." Accessed: Apr. 29, 2025. [Online]. Available: https://www.copyright.gov/title17/

[17] T. Rayna, L. Striukova, and J. Darlington, "Co-creation and user innovation: The role of online 3D printing platforms," *Journal of Engineering and Technology Management*, vol. 37, pp. 90–102, Jul. 2015, Doi: 10.1016/j.jengtecman.2015.07.002.

[18] MICHAEL WEINBERG, "WHAT'S THE DEAL WITH COPYRIGHT AND 3D PRINTING?," Jan. 2013. [Online]. Available: http://www.publicknowledge.org/it-will-be-awesome-if-they-dont-screw-it-up.

[19] J. Yuan, Y. Zhou, G. Chen, K. Xiao, and J. Lu, "Materials vs digits: A review of embedded anti-counterfeiting fingerprints in three-dimensional printing," *Materials Science and Engineering: R: Reports*, vol. 160, p. 100836, Sep. 2024, Doi: 10.1016/j.mser.2024.100836.

[20] Y. Gao, W. Wang, Y. Jin, C. Zhou, W. Xu, and Z. Jin, "ThermoTag: A Hidden ID of 3D Printers for Fingerprinting and Watermarking," *IEEE Transactions on Information Forensics and Security*, vol. 16, pp. 2805–2820, 2021, Doi: 10.1109/TIFS.2021.3065225.

[21] J.-U. Hou, D. Kim, W.-H. Ahn, and H.-K. Lee, "Copyright Protections of Digital Content in the Age of 3D Printer: Emerging Issues and Survey," *IEEE Access*, vol. 6, pp. 44082–44093, 2018, Doi: 10.1109/ACCESS.2018.2864331.

[22] M. Kurman, "Carrots, Not Sticks: Rethinking Enforcement of Intellectual Property Rights for 3D-Printed Manufacturing," *3D Print Addit Manuf*, vol. 1, no. 1, pp. 44–51, Mar. 2014, Doi: 10.1089/3dp.2014.0002.

[23] M. Rimmer, "Metal 3D printing: Patent law, trade secrets, and additive manufacturing," *Front Res Metr Anal*, vol. 7, Sep. 2022, Doi: 10.3389/frma.2022.958761.

[24] "3D printing and IP law." Accessed: May 04, 2025. [Online]. Available: https://www.wipo.int/en/web/wipo-magazine/articles/3d-printing-and-ip-law-39896

[25] X. Han, D. Zhu, X. Wang, T. Daim, and Y. Qiao, "Discovering technology opportunities based on the linkage between technology and business areas: matching patents and trademarks," *Technol Anal Strateg Manag*, vol. 35, no. 10, pp. 1324–1340, Oct. 2023, Doi: 10.1080/09537325.2021.2003773.

[26] Y. Zhang, B. Westerweel, R. Basten, and J.-S. Song, "Distributed 3D Printing of Spare Parts via IP Licensing," *Manufacturing & Service Operations Management*, vol. 24, no. 5, pp. 2685–2702, Sep. 2022, Doi: 10.1287/msom.2022.1117.

[27] R. Kumar, D. Choudhary, P. Bang, A. Dua, and K. S. Sangwan, "A Blockchain Technology based Framework for Environmental and Social Impact Authenticity of a 3D Printed Product," in *Procedia CIRP*, Elsevier B.V., 2023, pp. 281–286. Doi: 10.1016/j.procir.2023.02.048.

[28] Y. Zhang *et al.*, "A Decentralized Model for Spatial Data Digital Rights Management," *ISPRS Int J Geoinf*, vol. 9, no. 2, p. 84, Feb. 2020, Doi: 10.3390/ijgi9020084.

[29] Zhaofeng Ma, "Digital rights management: Model, technology and application," *China*

Communications, vol. 14, no. 6, pp. 156–167, 2017, Doi: 10.1109/CC.2017.7961371.

[30] B. Kading and J. Straub, "Utilizing in-situ resources and 3D printing structures for a manned Mars mission," *Acta Astronaut*, vol. 107, pp. 317–326, Feb. 2015, Doi: 10.1016/j.actaastro.2014.11.036.

[31] "Home - Mattereum." Accessed: May 04, 2025. [Online]. Available: https://mattereum.com/

[32] A. Rindfleisch, "The Second Digital Revolution," *Mark Lett*, vol. 31, no. 1, pp. 13–17, Mar. 2020, Doi: 10.1007/s11002-019-09509-4.

[33] "Discover STL files for 3D printing ideas and high-quality 3D printer models. | MyMiniFactory." Accessed: May 04, 2025. [Online]. Available: https://www.myminifactory.com/

[34] M. Klöckner, S. Kurpjuweit, C. Velu, and S. M. Wagner, "Does Blockchain for 3D Printing Offer Opportunities for Business Model Innovation?" *Research-Technology Management*, vol. 63, no. 4, pp. 18–27, Jul. 2020, Doi: 10.1080/08956308.2020.1762444.

[35] S. Kurpjuweit, C. G. Schmidt, M. Klöckner, and S. M. Wagner, "Blockchain in Additive Manufacturing and its Impact on Supply Chains," *Journal of Business Logistics*, vol. 42, no. 1, pp. 46–70, Mar. 2021, Doi: 10.1111/jbl.12231.

[36] M. Klöckner, S. Kurpjuweit, C. Velu, and S. M. Wagner, "Does Blockchain for 3D Printing Offer Opportunities for Business Model Innovation?" *Research-Technology Management*, vol. 63, no. 4, pp. 18–27, Jul. 2020, Doi: 10.1080/08956308.2020.1762444.

[37] J. Holmström, M. Holweg, B. Lawson, F. K. Pil, and S. M. Wagner, "The digitalization of operations and supply chain management: Theoretical and methodological implications," *Journal of Operations Management*, vol. 65, no. 8, pp. 728–734, Dec. 2019, Doi: 10.1002/joom.1073.

[38] K. Zheng, Z. (Justin) Zhang, Y. Chen, and J. Wu, "Blockchain adoption for information sharing: risk decision-making in spacecraft supply chain," *Enterp Inf Syst*, vol. 15, no. 8, pp. 1070–1091, Sep. 2021, Doi: 10.1080/17517575.2019.1669831.

[39] M. Li, L. Wang, and Y. Zhang, "A framework for rocket and satellite launch information management systems based on blockchain technology," *Enterp Inf Syst*, vol. 15, no. 8, pp. 1092–1106, Sep. 2021, Doi: 10.1080/17517575.2019.1669828.

[40] M. K. Lim, W. Xiong, and Z. Lei, "Theory, supporting technology and application analysis of cloud manufacturing: a systematic and comprehensive literature review," *Industrial Management & Data Systems*, vol. 120, no. 8, pp. 1585–1614, Jul. 2020, Doi: 10.1108/IMDS-10-2019-0570.