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The Impact of Blockchain Technology on Product Supply Chains in The Field of Industrial Design

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Abstract
The integration of blockchain technology into supply chain management presents a paradigm shift with the potential to revolutionize industrial product design. This research explores the capacity of blockchain to address inherent supply chain challenges, including lack of traceability, stakeholder distrust, limited transparency, outdated data sharing methods, and compliance issues. Blockchain's decentralized structure, immutability, and smart contract capabilities offer solutions by enhancing transparency, ensuring data integrity, automating processes, and fostering trust among stakeholders. The study investigates how blockchain implementation can optimize various facets of the industrial design product lifecycle, from raw material sourcing and design to production, distribution, and end-of-life management. Furthermore, it examines the implications of blockchain for promoting sustainability, ethical practices, and consumer trust, highlighting its role in creating more resilient, efficient, and transparent supply chain ecosystems. To understand the integration of blockchain technology into the supply chain of industrial design products, this paper systematically summarizes the status of blockchain technology, its main characteristics, and its potential applications in the field of industrial design. The analysis concludes that while challenges such as energy consumption and the need for standardization remain, the strategic adoption of blockchain technology can significantly redefine industrial design product supply chains, fostering innovation and sustainable growth.

Keywords : Blockchain Technology, Supply Chains (SCs), Industrial Design Products, Transparency, Digitalization.

1. Introduction

Supply chain management is a critical component of industrial product design, encompassing the flow of raw materials, products, information, and finances from end to end. Its significance is amplified in the global economy, where it directly influences an organization's performance, managing sourcing, procurement, manufacturing, distribution, and logistics to affect speed-to-market, product cost, service perception, and capital requirements. However, supply chain processes are increasingly complex, facing challenges such as managing multiple suppliers and logistics partners, rapidly changing customer demands, and rising operational costs. These complexities underscore the need for innovative solutions to enhance efficiency, flexibility, and responsiveness within supply chain operations.

Traditional supply chain models, characterized by centralized authentication, struggle with vulnerabilities to data tampering, information asymmetry, and difficulties in identifying responsibility. These shortcomings are exacerbated by evolving customer expectations, competitive pressures, geographically dispersed operations, and the emergence of e-commerce, which collectively demand greater transparency, traceability, and agility. The inability of outdated supply chains to provide adequate demand management, data visibility, and product tracking, coupled with their failure to mitigate risks and meet dynamic market requirements, necessitates a paradigm shift towards more resilient and transparent systems.

The fourth industrial revolution is characterized by rapidly evolving technology and a heightened demand for supply chain transparency and efficiency in organizations. Global supply chains have become increasingly complex as supply networks have grown to meet the needs of the global population. For instance, large corporations such as Total Energies and Walmart rely on approximately 100,000 suppliers each (TotalEnergies, 2022; Walmart, 2022), making supply chain visibility. A key issue is the lack of visibility within supply chains, which hinders proactive disruption management and presents opportunities to substitute genuine goods with substandard or counterfeit products. Many existing data systems are ill-equipped to validate synchronized and authenticated supply chain tracking throughout the logistics cycle

Digitalization and automation, incorporating technologies like the Internet of Things (IoT), robotics, big data, artificial intelligence, and blockchain, are emerging as transformative forces in supply chain management. These advancements offer the potential to enhance efficiency, reduce costs, improve customer satisfaction, and provide real-time visibility in supply chain operations. Blockchain technology has garnered attention for its capacity to enable secure and instantaneous information sharing, thereby improving transparency, reliability, traceability, and visibility across the supply chain. Despite challenges such as global economic instability and the need for a well-defined implementation framework, blockchain's unique features make it a promising tool for revolutionizing supply chain management in the industry 4.0 era.

2. Material and methods

This research employs a mixed-methods approach, combining qualitative and quantitative research strategies to provide a holistic understanding of blockchain technology's impact on industrial design product supply chains.

- A comprehensive literature review was conducted to synthesize existing knowledge on supply chain management, blockchain technology, and their applications in industrial design. This review involved the analysis of academic databases, industry reports, and case studies to identify key trends, challenges, and opportunities.
- Case studies of companies and initiatives that have implemented blockchain solutions in their supply chain operations were analyzed to provide real-world examples and insights. These case studies were selected based on their relevance to the industrial design sector and their representation of diverse applications of blockchain technology.
- Interviews were conducted with industry experts, supply chain managers, designers, and technology developers to gather qualitative data on the perceived benefits, challenges, and implementation strategies related to blockchain in industrial design.
- A conceptual framework for blockchain implementation in industrial design product supply chains was developed based on the literature review, case study analysis, and expert interviews. This framework outlines the key components, processes, and considerations for integrating blockchain technology into existing supply chain models.

3. Purpose of the study

This study aims to comprehensively investigate the impact of blockchain technology on product supply chains within the field of industrial design. The primary objectives include:

- Analyzing the potential of blockchain to enhance traceability, transparency, and authenticity in industrial design product supply chains.
- Evaluating the role of blockchain in addressing key challenges such as counterfeiting, supply chain disruptions, and the need for greater sustainability.
- Exploring the applications of blockchain across various stages of the industrial design product lifecycle, including design and production, distribution and logistics, and end-of-life management.
- Developing an understanding of how blockchain can facilitate collaboration, improve process efficiency, and foster consumer trust in the context of industrial design.
- Identifying the challenges and limitations associated with blockchain implementation in industrial design supply chains and proposing potential solutions.

4. Supply Chain Overview

The supply chain constitutes the integrated end-to-end flow of physical goods and the associated data pertaining to raw materials, products, information, and financial resources. This intricate network occupies a uniquely critical position within business operations, significantly influencing organizational performance. Supply chain management encompasses and actively participates in sourcing, procurement, manufacturing, distribution, and logistics activities, thereby impacting time-to-market, product cost structures, service quality perception, and organizational capital requirements. [1] Fundamentally, the supply chain integrates a series of often geographically dispersed and previously fragmented processes into a unified system designed to deliver value to the end customer, as illustrated in Figure 1.

As depicted in Figure 2, supply chain management has long been an integral element of industrial product design, playing a crucial role in ensuring the timely and efficient delivery of products and services to their intended recipients. However, its significance has become increasingly pronounced within the contemporary global economic landscape. Despite the numerous advantages afforded by effective supply chain management, it is not devoid of inherent challenges. Supply chain processes are confronted with escalating complexities, ranging from the coordination of multiple suppliers and logistics providers to the accommodation of rapidly evolving customer demands. Moreover, increasing expenditures related to transportation, raw materials, and labor, coupled with the imperative for enhanced efficiency and operational flexibility, have placed substantial pressure on supply chain operations to achieve desired outcomes, as detailed in Reference.[3]

Fig. 1. Supply chain and operation[2]

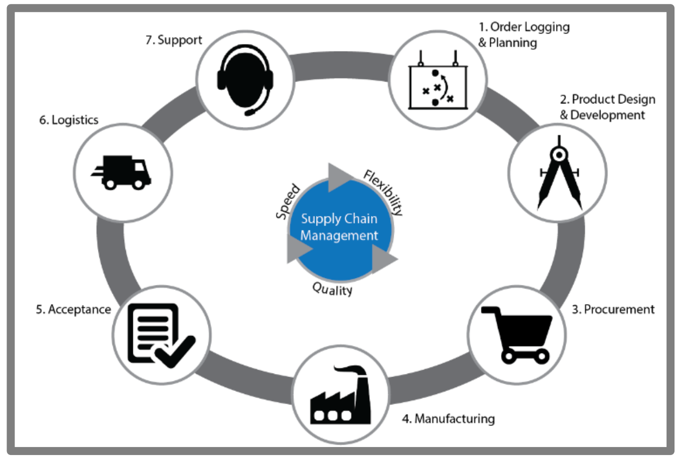


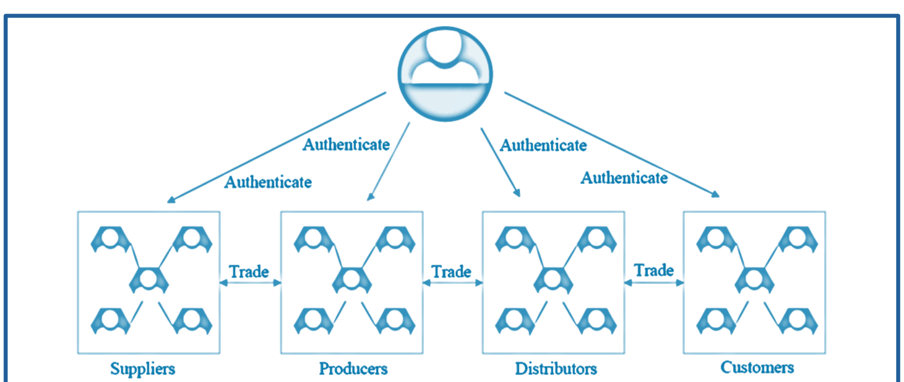
Fig. 2. Supply chain operations associated with industrial design products.[4]

5. Traditional Traceability for Supply Chain

In conventional supply chain authentication models, as illustrated in Figure 3, transaction validation is exclusively performed by a central, authorized entity. The inherent concentration of authority within this central organization necessitates a demonstrable level of autonomy and integrity. During supply chain operations, each node within the network maintains product traceability information within its proprietary system. For instance, supplier item data is stored in the supplier's warehouse database, while delivery records are managed by the logistics provider, resulting in a multiplicity of centralized data repositories. Current traditional traceability systems can be categorized into three primary types: enterprise-developed systems, third-party platforms, and government-established systems. In comparison to the latter two, enterprise-built systems typically require greater capital investment and present more complex operational and maintenance management challenges. Third-party platforms often lack specific relevance to individual enterprise needs and generally possess insufficient authority to engender widespread trust among both businesses and consumers. Government-established systems are predominantly utilized for the oversight of agricultural products and exhibit limited adaptability for diverse applications, [5] These three categories of traditional traceability systems, predicated on centralized information management, are inherently susceptible to the following practical limitations:

- Susceptibility to data manipulation and unauthorized alteration.
- Presence of information asymmetry across the network participants.
- Challenges in unequivocally identifying the responsible party in the event of discrepancies or issues.

Fig. 3. Traditional authentication model of a supply chain.[5]



6. Problems with traditional supply chain

The increasing complexity of contemporary supply chains is driven by evolving customer demands, competitive pressures, geographically dispersed operations, and the adoption of novel business paradigms, such as e-commerce. Over the preceding decade, the proliferation of e-commerce and portable digital devices has fundamentally reshaped consumer behavior, particularly in purchasing habits. There is growing consumer expectation for personalized products, streamlined and efficient shopping experiences, and transparent information regarding product value and provenance. While these demands present new opportunities for businesses, they simultaneously impose significant challenges on existing supply chain infrastructures. These legacy supply chain models struggle to effectively manage demand fluctuations, provide comprehensive data visibility across the entire value stream, or accurately track goods from raw material acquisition to final consumption, representing substantial operational complexities. Furthermore, the established technologies underpinning current supply chains often fail to provide adequate risk mitigation strategies, optimize cost efficiency, or adapt to rapidly changing market requirements. [1] The principal challenges inherent in current supply chains are summarized below:

6.1. Lack of Traceability:

Traceability has emerged as a critical imperative for modern supply chains in recent years, particularly with respect to enhancing customer service and improving the accuracy of business operations planning and forecasting. However, the deployment of a unified, centralized system within interconnected networks, especially those characterized by limited inter-organizational trust, presents significant obstacles. Instead, a fragmented landscape of discrete systems, comprising disparate databases maintained by individual stakeholders, impedes seamless product tracking throughout the entire supply chain network.

6.2. Stakeholder Distrust:

Trust constitutes a foundational element of effective supply chain management, and a robust supply chain network necessitates a strong underlying basis of mutual confidence. However, a lack of trust among participating entities represents a primary impediment to the advancement of supply chain networks. Consequently, most stakeholders within the network predominantly rely on third-party intermediaries to act as trust brokers and to validate transactions, which significantly elevates operational costs and diminishes process efficiency.

6.3. Limited Transparency:

Within the context of the supply chain, "transparency" refers to the degree to which all stakeholders possess a shared understanding of and access to accurate and sufficient information pertaining to products. A transparent supply chain network fosters enhanced trust among participants and ensures the integrity of both products and associated data. However, the isolated databases prevalent in current supply chain networks offer minimal transparency, and a substantial portion of valuable information is lost during the transfer of products and data between different stakeholders. Furthermore, issues related to inconsistent data sharing protocols, reliance on paper-based documentation, and inadequate system interoperability contribute to this limitation.

6.4. Outdated Means of Data Sharing:

Contemporary supply chain networks frequently rely on paper-based documentation for data exchange between numerous organizations. Critical documents, such as bills of lading, letters of credit, invoices, insurance policies, and various certifications, often must physically accompany the corresponding goods throughout their global transit. For example, a 2014 analysis by Maersk, a global transport and logistics company, revealed that approximately 200 distinct communications were required to complete a single shipment of frozen goods from Mombasa to Europe, resulting in a physical stack of documents roughly 25 centimeters in height, as cited in Reference [6] .This outdated and inefficient data sharing methodology frequently leads to delays for ships and aircraft in port when discrepancies arise between the physical cargo and the accompanying paperwork.

6.5. Compliance Challenges:

Businesses operating within modern supply chains face increasingly stringent regulatory standards aimed at ensuring the safety and quality of products and services delivered to consumers. However, under current supply chain processes, the collection of necessary information from diverse stakeholders and the development of a unified database capable of adhering to evolving regulatory requirements present significant logistical and technical challenges.

7. Digitalization and Automation in Supply Chain Management

Digitalization and automation represent fundamental technological transformations by reshaping contemporary supply chain management. Digitalization involves the comprehensive integration of digital technologies across all supply chain facets, while automation entails deploying machinery and software to execute tasks previously done manually. These technologies offer substantial advantages, including enhanced operational efficiency through streamlined processes and faster delivery cycles. Automation also improves accuracy in inventory tracking, order processing, and demand forecasting, minimizing human error.

Furthermore, digitalization and automation enhance customer service by enabling businesses to tailor products and services based on real-time data analysis of customer preferences. Increased visibility into supply chain operations, facilitated by technologies like IoT, allows for the identification of bottlenecks and optimization of inventory levels, enabling swift responses to market changes. Cost reductions are achieved through decreased reliance on manual labor, improved inventory management, and lower transportation expenses. Enhanced traceability, enabled by technologies like blockchain, improves product safety and quality and reduces counterfeiting risks while increasing overall supply chain transparency. Finally, digitalization and automation foster improved collaboration among supply chain partners through real-time data sharing, leading to optimized processes and reduced costs. Real-time information systems, leveraging IoT, robotics, big data, AI, ICT, and blockchain, are crucial for effective integration. While blockchain adoption faces challenges due to economic instability and a lack of standardized frameworks, its potential for secure information exchange in areas like cybersecurity, transparency, reliability, and traceability is significant in revolutionizing supply chain operations. [3]

7.1. Blockchain Technology

Blockchain technology, initially conceptualized by Nakamoto (2008) in the seminal Bitcoin white paper, revolutionized electronic transactions by obviating the necessity for trust through the implementation of a peer-to-peer network and a proof-of-work consensus mechanism to maintain a transparent and immutable public record of transactions. Evolving from traditional database technologies, blockchain constitutes a distributed ledger technology (DLT) that appends chronologically timestamped transaction records, fortified by cryptographic techniques and consensus protocols to ensure data integrity. While initially conceived for digital currency applications, the utility of blockchain technology has expanded significantly beyond monetary transactions.

As a DLT, blockchain offers a framework for the end-to-end updating and validation of product traceability data within supply chains. Cryptographic hash functions guarantee the integrity and completeness of recorded information, with each network node independently verifying data accuracy. The inherent immutability of blockchain enables the creation of real-time, tamper-proof records, thereby facilitating efficient communication within complex and often fragmented supply chain ecosystems. The decentralized architecture of blockchain allows for the instantaneous propagation of data updates across all network participants, providing a shared, auditable history and transparent ownership of transactions, thus enhancing efficiency and scalability. Although initially designed as open distributed ledgers, functional distinctions exist between various blockchain platforms, such as Bitcoin and Ethereum. [7]

Blockchain technology uniquely integrates features such as a decentralized structure, distributed nodes and storage, consensus algorithms, smart contract functionality, and asymmetric encryption to ensure network security, transparency, and visibility. This combination imbues blockchain with substantial potential to transform diverse supply chain (SC) functions, ranging from SC provenance and business process reengineering to security enhancement. [8]

Fundamentally, blockchain is an immutable and tamper-proof distributed ledger technology (DLT) operating within a shared and synchronized environment where all transactions undergo user validation and are inherently traceable. It establishes a decentralized ecosystem wherein all network members can interact securely without reliance on a central trusted authority, effectively eliminating the need for a central entity by validating and storing all transactions through distributed consensus mechanisms. [8]

The blockchain structure comprises a sequential chain of interconnected blocks, enabling straightforward tracing of transaction history through preceding blocks, thereby ensuring transparency and trustworthiness. Each block contains a unique identifier and incorporates the cryptographic hash of the prior block, guaranteeing transaction security. All transactions are validated and recorded by network users, time-stamped, arranged chronologically, linked to the preceding block, and rendered irreversible upon addition to the network. This comprehensive architecture establishes blockchain as a "trusted technology." A critical functionality contributing to blockchain's trustworthiness, security, and transparency is the "consensus mechanism." Records are embedded within blocks linked by hash values, and the decision to append a new block to the system is governed by the consensus protocol. Any attempt to alter an existing block necessitates that an adversary competes with all other users to construct a longer blockchain branch, a mechanism that, through collaborative validation, protects historical data integrity within the DLT. [8]

7.2. The Structure of Blockchain

A blockchain can be defined as a distributed, append-only data structure with inherent timestamping. This linked data structure chronologically connects data blocks, and its tamper-proof and unforgeable nature is enabled by cryptographic techniques, forming a distributed ledger technology (DLT). Generated data is stored within blocks, which are sequentially linked to form a chain. This structure, along with its underlying technology, ensures the security of data upload and ledger access by making the decentralized distributed ledger resistant to tampering and forgery. The block serves as the fundamental unit for data storage within the chain structure, containing all transaction information organized into a block header and a block body. [9]

Figure 4 illustrates the fundamental chained architecture of a blockchain network. Except for the initial genesis block, each subsequent block is uniquely identified by its hash, which includes the hash of the preceding block, thus establishing a chronological chain. This hashing mechanism significantly enhances data security. Typically, a block stores a set of timestamped transactions that have been validated by network stakeholders. Upon achieving consensus, the block is accepted and immutably stored by all participants in the blockchain, preventing subsequent modification. Consequently, trust and transparency in inter-organizational transactions are substantially improved.

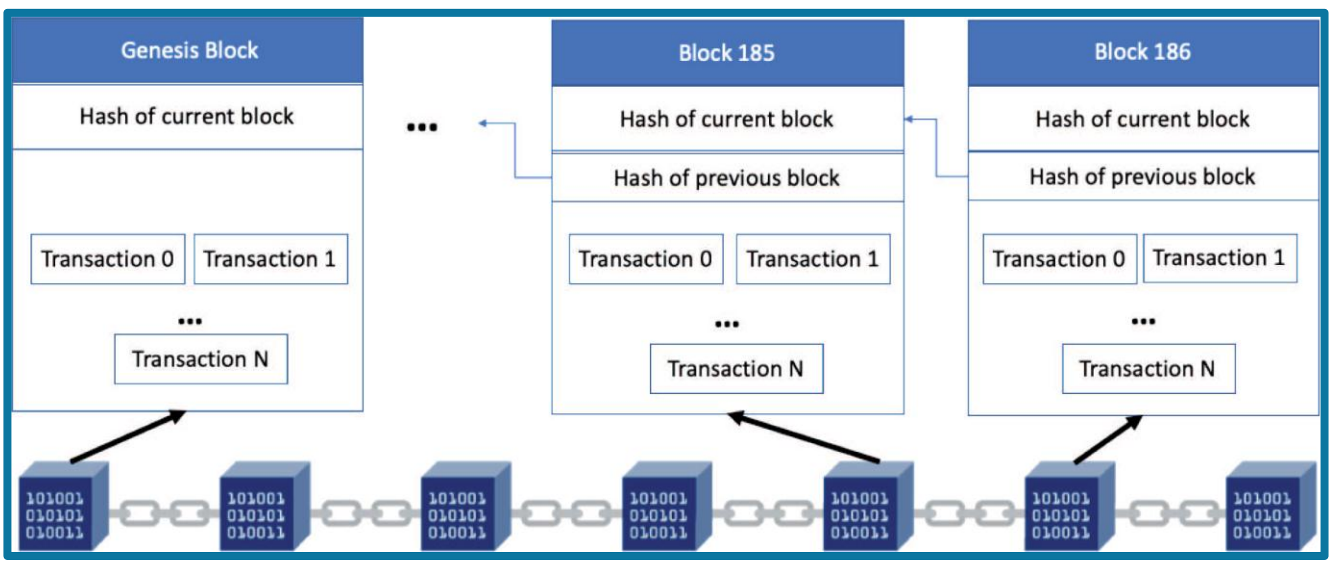


Fig.4 The structure of blockchain**.** [1]

The block header comprises elements such as the previous block hash, the Merkle Tree Root, and a timestamp. The previous hash, referencing the preceding block's hash, serves as the critical link between blocks. By following these previous hashes, each block can trace its lineage back to the genesis block, which has a null previous hash. This design makes deliberate and arbitrary alteration of a block exceptionally difficult, as any modification would change the block's hash and invalidate the subsequent chain. A timestamp provides verifiable evidence that data existed at a specific point in time. The Merkle Tree Root is a crucial component, representing the root of the Merkle tree, which structures the transactions within the block body. The block body contains all the transactions recorded within a specific time interval. These transactions undergo hashing and are organized by size to form the initial layer of the Merkle tree. Pairs of consecutive hash values are then iteratively hashed to form subsequent layers, continuing until a single root hash, the Merkle Tree Root, is generated. This hierarchical structure imbues blockchain technology with significant data security capabilities.

7.3. Characteristics of blockchain

The following characteristics delineate blockchain technology as a unique and promising paradigm for future industrial applications: [8]

7.3.1. Decentralization: Data accessibility, monitoring, storage, and updating are distributed across multiple systems, eliminating the reliance on a trusted central authority for transaction verification. Consensus mechanisms ensure transaction processing and validation by network nodes, each maintaining an equivalent copy of the digital ledger.

7.3.2. Transparency: Data recording and storage on the network are subject to network-wide consensus, ensuring visibility and traceability throughout the data lifecycle. Once most nodes reach agreement, transactions are immutably stored, and the ledger is updated. Any network modifications are publicly auditable, guaranteeing transparency.

7.3.3. Immutability: Blockchain employs time-stamping and cryptographic controls to ensure data immutability. Verified transactions are permanently recorded in the ledger, providing an auditable history of all prior transactions on the chain, thereby enhancing visibility and accountability.

7.3.4. Irreversibility: Every transaction executed on the blockchain generates a definitive and verifiable record maintained across the distributed network.

7.3.5. . **Autonomy**: Each node within the blockchain network possesses the independent capability to securely access, transfer, store, and update data without requiring third-party intervention.

7.3.6. . **Open Source**: Blockchain platforms often provide open-source access to all network participants, potentially with defined hierarchical permissions.

7.3.7. Pseudonymity: While data transfer occurs between network nodes, the direct identity of individual participants can remain obscured.

7.3.8. Ownership and Uniqueness: Every digital asset exchanged on the blockchain has its ownership records secured by a unique cryptographic hash.

7.3.9. Provenance: Each product can possess a digital record on the blockchain, establishing its authenticity and origin.

7.3.10. Contract Automation (Smart Contracts): These are small, self-executing computer programs that automate contract execution. They offer enhanced security and reduced transaction costs compared to traditional contracts. Smart contracts are typically programmed with predefined conditions, rules, penalties, and actions applicable to all involved parties, enabling rapid response operations in supply chains by automatically triggering actions upon the fulfillment of specified conditions.

7.3.11. Traceability: Transaction information is permanently recorded on the blockchain, and each update can be traced back to its origin, resulting in a more efficient and transparent network.

7.3.12. Trustless Environment: Blockchain facilitates transactions between mutually unfamiliar parties by employing consensus mechanisms to validate transactions through the distributed and continuously updated ledger, eliminating the need for inherent trust.

7.3.13. Persistence: The inherent infrastructure of blockchain ensures the authenticity and immutability of network data. Transactions recorded on the ledger are persistent due to their distribution across the network, where each node maintains and controls its data records.

7.3.14. Pseudonymity: Network participants can be assigned virtual identities, and sensitive data is not monitored by any external central authority, providing a degree of anonymity within the trustless environment.

7.3.15. Auditability: All recorded transactions are timestamped and stored on the immutable ledger, allowing for retrospective tracing of information due to its persistent nature. The level of auditability varies depending on the blockchain type, with public blockchains offering the highest degree and private blockchains the lowest.

7.3.16. Validity: Broadcasted transactions undergo validation by network nodes and do not require execution by every node. Falsifications or inconsistencies can be readily detected through the consensus process.

7.3.17. Tamper-Resistance: Transactions are considered tamper-proof both during and after the block generation process. The chain-on-structure of blocks, where each is cryptographically linked to the previous one, necessitates altering numerous parameters across the entire chain for successful manipulation, making such attempts easily detectable.

The impact of blockchain technology on supply chain operations begins with the recognition of being Blockchain technology is a cutting-edge, decentralized, and distributed ledger technology designed to ensure the confidentiality, integrity, and availability of transactional data. Functioning as a shared, open, and distributed ledger, it securely stores and records data and transactions, cryptographically secured across a peer-to-peer network. This digital shared ledger, distributed across the network, creates immutable records that, once appended, cannot be altered without subsequent changes to preceding records (typically requiring consensus from participating parties), thereby enhancing security for business operations. [8]

Blockchain's distributed consensus mechanism provides participating entities with real-time awareness of all events and transactions, establishing an irrefutable record on the public ledger. Its decentralized, verified, and immutable nature has disrupted numerous sectors, including banking, supply chain operations, real estate, insurance, healthcare, electronic health records, copyright, music, and renewable energy, with its influence continuing to expand. Beyond transforming supply chains across various industries, blockchain also enhances the functionality and security of existing digital platforms, including the Internet of Things (IoTs) and other Industry 4.0 technologies. Recognizing the diverse privacy and security requirements across industries, blockchain architectures can be tailored into three primary structures: public (permissionless), private (permissioned), and consortium (hybrid). [8] **Public blockchains** offer open access to all network users via peer-to-peer networks. **Private blockchains** provide role-based data access and leverage cloud networks for increased flexibility, with potential applications in areas like social media analytics. **Consortium blockchains** combine attributes of both public and private structures, offering a balance between accessibility and control.

While collaboration and information sharing are vital for supply chain partners, organizations prioritize the protection of proprietary data from competitors, often favoring private ledgers due to concerns about data exposure and competitive intelligence leakage. The choice between private and public blockchain deployment hinges on the specific business environment and desired competitive advantages. Organizations can assess blockchain's potential to reduce paper-based processes, enhance traceability methodologies, and secure provenance data. Blockchain technology is anticipated to undergo further advancements in proofs of concept, standardization efforts, collaborative initiatives, and integration with complementary technologies. [7]

8. Blockchain Technology for Supply Chain Functions

Supply chain management (SCM) constitutes a substantial sector and forms the fundamental framework of every industry. However, conventional SC systems exhibit limitations in versatility and transparency, rendering them inadequate to address the evolving needs and demands of the future, resulting in significant operational overheads related to error rectification, costs, administrative processes, and fraud mitigation. [14]

8.1. Benefits Of Using Blockchain in Supply Chains

Within the context of Industry 4.0, blockchain technology has been proposed to organize records in a distributed architecture utilizing a consensus mechanism. It possesses the potential to transform SCM through its inherent characteristics of transparency, authenticity, trust, security, cost reduction, disintermediation, operational efficiency, and waste minimization. Furthermore, all transactions facilitated by blockchain offer enhanced efficiency, security, economic viability, and transparency. Consequently, it is widely acknowledged that the distributed nature of blockchain aids in mitigating risks within the SC associated with piracy, cyber intrusions, system vulnerabilities, costly compliance with governmental regulations, and contractual disputes. Blockchain also facilitates real-time order settlement and the automation of manufacturing tasks through the implementation of smart contracts. Table 1 provides a summary of select benefits derived from blockchain implementation in SCs. [8]

Table (1) Benefits of blockchain in SCs

1	Data management	- Enables calibration of data located across diverse SCs. - Improves security of data stored. - Real time capturing all information is done
2	Improves transparency	- Helps track the status of an item during a process - Automates data analysis activities -End to end transparency based on permission level via hierarchy
3	Improves response time Smart contract management	- Creates a dynamic and real time SC with better utilization of its resources - Customized and individual contracts can be defined for each function and can be coordinated with each other - Helps in process design for business operations - Improves visibility and eliminates the need of intermediary
4	Operational efficiency	- Improves end to end speed of SC process - Identifies bugs and issues in the beginning to make the process robust
5	Disintermediate	- Leads to an uninterrupted chain of transactions - Increases speed - Increases trust among stakeholders of process
6	Immutability	- Consensus mechanism for all modifications - Ensures security of all transactions
7	Intellectual property Management	- Intellectual Property Protection and registration

Blockchain technology enhances supply chain operations by improving efficacy, efficiency, and transparency, while simultaneously reducing transactional time and costs. Several key benefits accrue from its adoption:

8.1.1. Enhanced Traceability:

Blockchain significantly improves supply chain traceability by establishing a fully auditable record of all items moving through the network. When integrated with IoT devices, such as RFID, a blockchain-enabled supply chain can automatically collect granular, item-level data for vast quantities of products in real-time. This information, coupled with timestamps and location data, forms a comprehensive, accurate, and readily accessible audit trail from the product's origin to the end consumer. Furthermore, the inherent immutability of blockchain data and the digital signatures required for confirming information ownership ensure a secure and complete history of any item within the entire supply chain. In the event of a compromised product, this enhanced traceability facilitates rapid identification of the issue's source, thereby reducing product recall costs and improving disruption resolution among stakeholders. Advanced traceability also bolsters stakeholders and customer confidence in a product's authenticity and quality.

8.1.2. Improved Transparency:

Blockchain technology provides robust identity management within the supply chain, enabling all authorized parties to ascertain who performed specific actions, at what time, and in what location. This information is securely stored and shared across distributed ledgers, offering convenient access to involved and authenticated stakeholders. The integration of physical and digital flows throughout the supply chain enhances connectivity among multiple trading partners. Consequently, a blockchain-enabled supply chain, with its transparent and comprehensive record of product flow, empowers businesses to make more accurate forecasts and informed decisions. Moreover, improved transparency serves as a powerful deterrent against fraud and counterfeiting.

8.1.3. Boosted Efficiency:

A primary driver for blockchain implementation is the replacement of outdated, paper-intensive processes. As a benefit of digitalization, the logically centralized data ledger provides up-to-date local copies to all authorized stakeholders within the network. All transactions are committed and immediately validated by participating parties, with data automatically synchronized across each party's local leader. Blockchain technology enhances the security and speed of maintaining transaction quality and associated data by minimizing human error and eliminating the need for third-party intermediaries and local ledger reconciliation. Finally, autonomous and self-executing blockchain-based smart contracts replace cumbersome manual processes and enhance flexibility in supply chain management.

8.1.4. Greater Security:

Blockchain technology exhibits significant resilience against hacking attacks that commonly threaten centralized databases managed by intermediaries (e.g., banks). Its architecture necessitates tampering with the specific targeted block and all preceding blocks throughout the entire transaction history for a successful breach. Thus, blockchain provides a more secure environment for managing numerous business activities and transactions.

8.1.5. Enhanced Trust:

Transactions within a blockchain-based supply chain are created and recorded through peer-to-peer interaction, with trust established through associated digital signatures. Additionally, a reliable identity management system enables the capture of time, location, and other relevant data at every action concerning a product within the supply chain. The real-time synchronization of all data across all stakeholders within the supply chain network fosters enhanced trust among participating entities.

8.1.6. Easy Compliance:

A blockchain-enabled supply chain network meticulously records all transactions with precise details, including timestamps, environmental conditions, and location. These accurate, tamper-proof records serve as a reliable source for a business's data integrity and can be readily accessed to facilitate regulatory adherence and compliance.

8.2. Enhancing Industrial Product Lifecycle Visibility Through Blockchain Technology

The capabilities of blockchain as a distributed and decentralized database extend beyond the mere reduction of reliance on central authorities and intermediaries. The inherent decentralization and immutability of blockchain, coupled with its identity protection features, afford various network nodes the opportunity to record, utilize, and verify information on a shared public ledger while maintaining participant pseudonymity. Blockchain technology enables manufacturers to monitor products throughout their entire lifecycle, facilitating the collection of essential data for enhanced product design, manufacturing processes, sales strategies, usage analysis, and end-of-life recovery. Traditionally, comprehensive data sharing across a product's lifecycle has been either prohibited or practically infeasible. However, blockchain has the potential to transform the way product lifecycle data is captured, processed, and utilized. Diverse stakeholders or network nodes can actively participate in the collection, verification, and application of product lifecycle data, governed by smart contracts embedded within the system. These smart contracts define the conditions for data collection, the responsible parties, data usage protocols, associated transaction fees, and incentivization mechanisms. While blockchain offers a viable solution for improving the feasibility of shared product lifecycle data, implementation challenges remain. Facilitating such data sharing can enable corporations to more effectively integrate sustainability principles into their business models. A transparent and traceable product lifecycle can further optimize material loops, reduce waste generation and emissions, and foster engagement among governments, stakeholders, and end-users. Figure 5 illustrates the potential for integrated information flows throughout the product lifespan enabled by blockchain technology. [15]

Blockchain technology can underpin shared, product-centric information management platforms, thereby facilitating the utilization of product lifecycle data by diverse stakeholders, particularly within the durable and capital goods industries. In the pharmaceutical sector, blockchain can contribute to enhanced management of public healthcare data, user-centric medical research, and the combatting of drug counterfeiting. Furthermore, blockchain technology can support the development of smart cities through the secure sharing of data from interconnected devices. Additional applications include

(1) streamlining paperwork processing in global container shipping, (2) identifying counterfeit products within pharmaceutical supply chains, (3) facilitating origin tracking in the food supply chain to address foodborne illness outbreaks, and (4) enabling real-time monitoring of sensor-equipped shipments in IoT-enabled supply chains. These applications can collectively contribute to environmental and social sustainability. Within the automotive industry, blockchain-based Vehicle Identity (VID) systems can be utilized for vehicle-to-everything communication, traffic management optimization, carbon emission reduction initiatives, facilitated vehicle maintenance, and the sharing of data from autonomous vehicles, among other potential applications.[16]

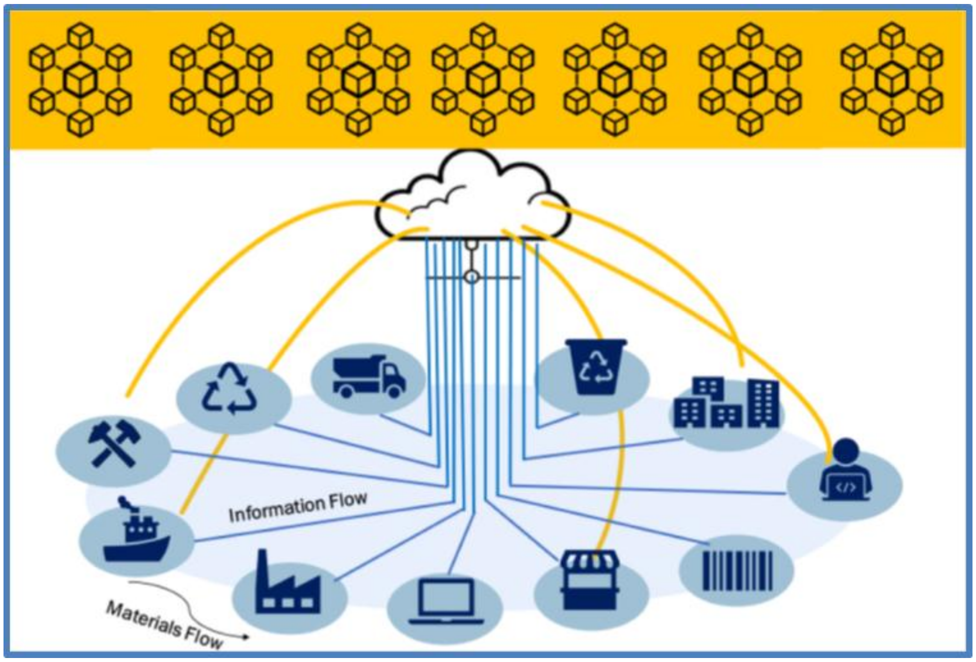


Fig. 5. Integration of information flow and material flow possible by blockchain[15]

9. The Role of Blockchain Technology in Industrial Product Supply Chains

Blockchain technology offers the potential to transform major supply chain (SC) functions, including SC reengineering, security, resilience, provenance, process management, and product management. [8]

9.1. Supply Chain Provenance

Integrating blockchain technology with the Internet of Things (IoTs) enables granular provenance tracking of physical goods within complex, inter-organizational, or internationally spanning SCs. This is achieved through certifiability, traceability, verifiability, and tractability of product information, ensuring origin and authenticity assurance, and maintaining integrity across the entire SC [8]. Drawing parallels to its traditional use in the art world, SC product provenance encompasses a comprehensive record of ownership, all transactions, and activities related to raw materials and finished goods throughout the supply chain. This record includes detailed information regarding location, handling entities, and the timing of each asset manipulation. In this context, "provenance" is defined as the collection of all recorded activities (potentially stored on a blockchain) that verify the origin of all material inputs and processes within the SC, spanning procurement, manufacturing, packaging, warehousing, transportation, and customer relationship management. Leveraging blockchain technology to capture and validate product provenance information enhances SC transparency and trust in next-generation digital ecosystems. Applications include improving traceability and visibility, supporting sustainability and recycling initiatives, enhancing process efficiency, and utilizing smart contracts to disintermediate SC actors. [7]

9.2. Supply Chain Resilience

Blockchain technology enhances SC resilience by mitigating the impacts of disruptions, enabling a proactive approach to risk management, and providing multi-layered protection for the SC network. The structural design of blockchain facilitates the capture of both organizational and network-level risks associated with any SC. [8]

9.3. Supply Chain Reengineering

Blockchain technology enhances SC transparency and visibility, enables process automation, eliminates intermediaries, and facilitates real-time tracking through traceability, privacy, and data management techniques, all of which are fundamental to SC reengineering. A properly reengineered SC can achieve synchronized tracking information across all business areas. Furthermore, the utilization of smart contracts can further reduce the time and cost associated with SC reengineering. [8]

9.4. Security Enhancement

Blockchain technology enables authentication, confidentiality, privacy, and access control; data and resource provenance; and integrity assurance within its service provision. It also facilitates the development of risk control analytics frameworks to analyze the interrelation between business, information, and engineering domains, providing an analytical perspective on digitalization within the SC. Its scalability allows blockchain to provide robust risk management even for large production enterprises, offering enhanced cybersecurity and performance compared to traditional IoT systems or security services.

9.5. Business Process Management

Blockchain technology facilitates efficient business process management through smart contracts by codifying the flow of control and business logic of interorganizational processes. The integration of blockchain with smart contracts also enables hyperconnected logistics. These controls are activated by triggers, acting as a bridge between enterprise applications and the blockchain. Proper smart contract implementation for modification or payment requests can automatically trigger process flows based on appropriate approvals, achieving speed, trust, and improved business performance. Blockchain technology can also be effectively utilized for customer-order-process management (COM), enhancing order efficiency, traceability, and visibility, as well as enabling asset management through its "proof of concept algorithm," which ensures transparency, reliability, and efficiency.

9.6. Product Management

Blockchain integration with SCs improves cycle time, productivity, and quality; creates new business opportunities; and enables product differentiation. Research has explored efficient product deletion and price management through blockchain technology. [8]

- **Product Deletion:** Blockchain facilitates product deletion processes, including recognition, analysis, revitalization, evaluation, decision-making, and implementation, through real-time tracking, multi-layered data management, improved demand forecasting, risk reduction, and automated decision-making. The information stored on the blockchain can be used to analyze company policies related to product deletion and the circular economy.
- **Price Tracking in Product Distribution**: Traditional price tracking systems lack transparency and do not provide an end-to-end view of price variations across the SC, typically only displaying the final consumer price. Blockchain technology can enable consumers to access detailed pricing information from raw materials to distributors, promoting price transparency by disseminating honest information from all stakeholders.

9.7. Sustainability and Recycling

Blockchain technology enables SC participants to accurately assess the environmental impact of products throughout their lifecycle, promoting a comprehensive understanding and facilitating a circular economy. The "triple retry model," combining blockchain with end-of-life goods data and integrating recycling, redistribution, and remanufacturing processes with blockchain's trust, traceability, and transparency features, enables circular SC models. This allows manufacturers to improve component efficiency and repurpose materials, contributing to resource conservation and waste reduction. Furthermore, blockchain enables businesses to validate sustainability claims, enhancing credibility and acceptance. It also has the potential to influence consumer behavior by providing product-to-sale traceability and incentivizing recycling through rating and reward systems. [10]

9.8. Process Efficiency

Blockchain technology can significantly enhance process efficiency within SCs. Accountable businesses are increasingly interested in traceability methods that ensure sustainability, product lifecycle transparency, waste reduction, carbon footprint tracking, and fair-trade practices. Wang et al. [17] demonstrate that companies piloting blockchain technology experience significant improvements in sales growth and reduced product returns. These positive outcomes are attributed to improved coordination between upstream and downstream supply chain activities and enhanced channel management. A blockchain simulation study revealed a remarkable 65% reduction in processing time for placing new orders and a 60% reduction in overall operational time, reducing warehousing space utilization and improving visibility across the supply chain. [18]

9.9. Consumer Behavior

Consumer behavior is increasingly oriented towards sustainability and ethical considerations, with many consumers seeking information about product origins. However, brands often face challenges in providing complete transparency. Xu and Duan [19] indicate that consumers have developed a high sensitivity to environmental issues, with approximately 20% of customers preparing to pay a premium for eco-friendly products. This finding suggests that a significant segment of consumers is willing to prioritize sustainability and ethical considerations in their purchasing decisions. Consumer preferences are also shifting toward more ethical practices. However, consumers often face information asymmetry regarding product origins and production processes, leading to potential risks. Proactive communication of ethical practices, transparency initiatives, and quality control measures are crucial for building consumer confidence. Privacy and security are also critical factors influencing consumer purchase decisions. Technologies like smartphone barcode scanning empower consumers to verify product information and trace origins. [20] Companies are increasingly participating in blockchain traceability systems to enhance consumer trust and minimize perceived risks. [17] Blockchain challenges traditional business models by introducing new value exchange options and enabling companies to differentiate themselves through transparent SC processes.[21, 22, 17].

9.10. Transparency and Traceability in Supply Chains

A significant contribution of blockchain technology to SCs is its ability to provide enhanced transparency and traceability. Blockchain's decentralized and immutable ledger ensures secure recording of all transactions and product movements, enabling tracking throughout the entire product lifecycle. This level of transparency is particularly valuable in industrial design for ensuring material and component quality and compliance. [23, 24] In manufacturing, blockchain can track raw material sourcing, monitor production processes, and verify component authenticity, aiding in identifying bottlenecks and enabling rapid responses to recall or quality issues [25,26].

10. Applications for Blockchain Technology in the Industrial Design Sector

Blockchain technology has the potential to resolve bottlenecks, pave the way for future research, and address problems using shared, secure, distributed, and permissioned transaction ledgers, making it a crucial force in research across various industrial sectors. Blockchain facilitates chain management, improves project management, enhances chain sustainability, models relationships, develops new products, and coordinates across chains globally. It also stimulates innovation in business modeling and value propositions, particularly among startups. Open-source software, new applications, and the elimination of third-party applications can further foster industrial innovation. Thoughtful application of blockchain systems can deliver significant benefits. Key applications and their impact include:

10.1. Manufacturing Sector

Blockchain facilitates the shift towards shared and distributed systems in manufacturing ecosystems through cross-enterprise frameworks, supporting enhanced knowledge sharing. Blockchain integration enables companies to build flexible and scalable businesses at lower costs in a more secure, effective, and well-controlled manner, increasing profitability and competitive ability through real-time transparency and cost savings. It also supports agile manufacturing practices, enabling product customization, smart automation, and improved employee empowerment. Examples include resolving issues of counterfeit products in additive manufacturing and reducing shipping costs through SC network implementation. In the automotive sector, blockchain can create distributed framework models to address demands for integrated, personalized, and on-demand services through connected, shared, and autonomous environments, ensuring SCM, security, evidence integrity, secure storage, mobility solutions, automated maintenance, auditability, transparency, execution speed, and cost reduction throughout the entire automotive lifecycle.

10.2. Enhancing Product Design and Production

Blockchain technology plays a pivotal role in the design and production phases of industrial design. Integrating blockchain with Product Lifecycle Management (PLM) systems ensures all stakeholders have access to accurate and up-to-date information, leading to more efficient design processes and better decision-making. [27 ,28] Blockchain can also facilitate the secure sharing of design data and intellectual property, crucial in industries where design integrity and confidentiality are paramount. [29 ,30]

10.3. Streamlining Distribution and Logistics

The distribution and logistics phases of SCs can significantly benefit from blockchain technology. Smart contracts can automate payment processes, track shipments, and verify delivery conditions, reducing the need for intermediaries and minimizing disputes. [31 ,32] Blockchain also enhances logistics efficiency by providing real-time visibility into the movement of goods, particularly valuable in complex global SCs where delays can have significant financial implications, enabling companies to optimize logistics operations and improve overall SC resilience.

10.4. Enabling Circular Economy and Sustainability

Blockchain technology supports the transition to a circular economy by enabling the tracking and management of resources throughout their lifecycle. In industrial design, this facilitates the design of products with reuse and recycling in mind, as their entire lifecycle can be monitored and optimized. [33, 34] Furthermore, blockchain can facilitate the creation of digital twins for products, allowing manufacturers to simulate and analyze the environmental impact of their designs, leading to more sustainable design practices and reduced waste throughout the SC. [35]. The applications of blockchain technology in the industrial design sector are summarized in Table 2

Table2: Applications for Blockchain Technology in the Industrial Design Sector

	Aspect	Impact
1	**Transparency and Traceability**	**Provides end-to-end visibility of product lifecycle**
2	**Design and Production**	**Facilitates secure data sharing and collaboration**
3	**Distribution and Logistics**	**Automates payment processes and optimizes logistics operations**
4	**Circular Economy**	**Enables tracking and management of resources for reuse and recycling**
5	**Integration with Other Technologies**	**Enhance predictive analytics and supply chain efficiency**

11. Addressing Challenges and Limitations

While blockchain technology presents substantial advantages for supply chains within industrial design, certain challenges warrant consideration. A primary concern pertains to the considerable energy expenditure associated with specific blockchain protocols, which can pose significant environmental consequences. However, ongoing research and development efforts are actively focused on the creation of more energy-efficient blockchain solutions. [36, 33]

Another significant challenge lies in the imperative for standardization and interoperability across disparate blockchain systems. As the adoption of blockchain technology proliferates among enterprises, the establishment of common standards is crucial to ensure seamless integration and efficient data exchange throughout the interconnected supply chain. [24, 37]

12. RESULTS AND DISCUSSION

The research findings indicate that blockchain technology has significant potential to transform industrial design product supply chains. Key results include:

- Blockchain enhances traceability and transparency by providing an immutable record of product information, from raw material sources to end-user delivery. This improves product authenticity, reduces counterfeiting, and enables quicker identification of issues in the supply chain.

- Blockchain facilitates secure data sharing and collaboration among stakeholders, leading to more efficient design and production processes. It also protects intellectual property and ensures that all parties have access to accurate and up-to-date information.
- Smart contracts automate payment processes and optimize logistics operations, reducing the need for intermediaries and minimizing disputes. Blockchain also provides real-time visibility into the movement of goods, improving supply chain resilience.
- Blockchain supports the transition to a circular economy by enabling the tracking and management of resources throughout their lifecycle. This promotes sustainable design practices, reduces waste, and allows for the creation of digital twins to analyze the environmental impact of products.
- Consumer trust is increased through blockchain's ability to provide verifiable product information and ethical sourcing practices. Consumers are increasingly demanding transparency and sustainability, and blockchain can help companies meet these expectations.

13. Recommendations

Based on the research findings, the following recommendations are proposed:

- Increased adoption of blockchain technology in industrial design product supply chains to enhance transparency, traceability, and authenticity.
- Development of industry standards and interoperability frameworks to ensure seamless integration and data exchange between different blockchain systems.
- Further research and development of energy-efficient blockchain solutions to address environmental concerns related to energy consumption.
- Exploration of innovative applications of blockchain in areas such as product lifecycle management, circular economy initiatives, and consumer engagement.
- Collaboration between industry stakeholders, technology developers, and policymakers to create a supportive ecosystem for blockchain implementation in the industrial design sector.

14. Conclusions

Blockchain technology offers a powerful solution to address the challenges facing contemporary industrial design product supply chains, including issues related to traceability, transparency, and authenticity. The implementation of blockchain can significantly enhance various aspects of the supply chain, from raw material sourcing and design to production, distribution, and end-of-life management, leading to improved efficiency and reduced costs. Blockchain's capacity to facilitate secure data sharing and protect intellectual property fosters collaboration and innovation within the industrial design sector. Technology plays a crucial role in promoting sustainability and ethical practices by enabling the tracking of product lifecycles, ensuring responsible sourcing, and empowering consumers to make informed choices. While challenges such as energy consumption and the need for standardization must be addressed, the strategic adoption of blockchain has the potential to redefine industrial design product supply chains, driving positive transformation and fostering a more resilient, transparent, and sustainable industry.

In conclusion, blockchain technology has the potential to revolutionize supply chains in the field of industrial design by providing transparency, traceability, and efficiency. Its ability to enhance collaboration, streamline logistics, and support sustainable practices makes it a valuable tool for companies looking to stay competitive in a rapidly evolving global market. As technology continues to mature, its impact on supply chains is expected to grow, driving innovation and excellence in industrial design.

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