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Hyperledger Fabric for the (digitalized) lifecycle of construction products: Applied review on fastening technology

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Abstract

Blockchain technology is a digital decentralized data ledger recording transactions in an encrypted format. Its implementation can potentially hold significant advantages for the built environment, particularly in manufacturing and building product usage aligned with Building Information Modeling (BIM). This paradigm shift toward decentralized transactions can foster security, reliability, and accountability. Hyperledger Fabric (HLF), an enterprise-grade distributed ledger, offers a modular, scalable, and confidential digital framework. This article introduces HLF-based workflows to address inefficiencies in BIM and fastener product lifecycle management, such as fragmented data handling and limited process automation. Leveraging chaincodes linked to BIM models, HLF simplifies, enhances transparency, and automates construction product lifecycle processes. Contract data and execution details are managed through a blockchain stored in a common data environment (CDE) and linked to chaincodes. The article presents the conceptualization and implementation of automated workflows, emphasizing efficiency and transparency. While showcasing successful deployments, it also highlights areas for future improvement and development. The proposed framework represents a pioneering step toward a decentralized cooperative environment in the construction industry, aligning with the transformative potential of blockchain technology.

KEYWORDS

blockchain technology, construction products, fastening technology, Hyperledger Fabric, lifecycle

1 | INTRODUCTION

The construction sector is witnessing a growing reliance on industrially prefabricated construction products as a means of enhancing total-cost efficiency, speed, circularity, and sustainability.[1,2] This trend is accompanied by a corresponding shift toward data-driven digital environments. In addition, an essential element of modern construction is the use of fastening technologies for the assembly of various components, including structural connections, building shell components, and non-structural components such as partition walls, suspended ceilings, door and window frames, and electromechanical equipment.[3,4]

Significant attention is devoted to the rapid development of innovative solutions and the swift establishment of standards at the national and international levels. Currently, the numerous options of the fastenings manufacturing branch in terms of construction products and their variants necessitate dependable information and certification for each element's installation and performance.[5] In Europe, the pertinent Construction Products Regulation[6] establishes a methodology for evaluating the technical performance of products, facilitating free cross-border trade and providing third-party-verified characterization regarding various technical attributes, including load capacity, fire resistivity, health risks, durability, and environmental impact. As the requirements for sustainable and circular construction escalate, lifecycle and reusability information must be easily traceable.[7] In addition, even after installation, the performance monitoring of fastenings remains crucial as it controls the function and stability of all high-value and safety-critical attachments.[8,9] Ultimately, the optimal selection and utilization of fastenings necessitate a robust track record of product lifecycle and logistical data.[10]

Among the most recent technological innovations, blockchain technology has emerged as a transformative force with the potential to reshape various industries. Due to its decentralized and transparent nature, it offers opportunities to optimize processes, enhance security, and foster trust in the digital ecosystem.[11] Blockchain technology has the potential to bring about significant changes in the construction industry. Indicatively, blockchain technology could be employed to automate contract execution and facilitate the availability of transparent, immutable, and digitally accessible information, which would serve to reduce delays, human errors, interface conflicts, and defects.[12] In conclusion, it can provide a secure platform for the management of design, construction, supply chains, and operational assets. In the context of construction products, a number of benefits can be identified,[13] particularly in relation to the specific challenges and opportunities presented by the digitalization of fastening technology (e.g., respectively in data integration, stakeholder adoption, scalability, collaboration, sustainability, and efficiency). This article provides an elaboration on the applicability of blockchain technologies in various lifecycle aspects of fastening technology. First, it presents a topic-oriented overview of blockchain technology in construction, with the objective of establishing a knowledge foundation. The article then proceeds to examine the specific paradigms of Hyperledger Fabric (HLF) that are utilized across the various stages of a post-installed fastening product's lifecycle. The focus of this study is on international production and use in the European construction industry and market. As explained below, a structured systematic review with suitable analytical tools is employed to achieve this objective.

2 | BLOCKCHAIN TECHNOLOGY

Originally conceptualized as the underlying framework for cryptocurrencies, blockchain technology has evolved into a robust and decentralized system with applications across various industries. Blockchain technology is a distributed ledger that records transactions in a secure and transparent manner. Each participant in the network possesses an identical copy of the entire transaction history, which is regularly synchronized through the consensus mechanism.[14] The cryptographic principles that form the basis of blockchain technology ensure the immutability, decentralization, and transparency of transactions, making it an attractive solution for addressing trust and security concerns in a range of domains.[15] One of the fundamental characteristics of blockchain is immutability. Once a block of data is added to the chain, it becomes practically impossible to alter or delete. This immutability is achieved through the use of cryptographic hashing, where each block contains a reference to the previous block, creating a chain of interconnected blocks. Consensus mechanisms such as proof-of-work or proof-of-stake ensure agreement among network participants regarding the validity of transactions,[16] enabling the consistent and synchronized distribution of the ledger across all nodes in the decentralized network.[17,18] Furthermore, blockchain's cryptographic security protects data integrity and confidentiality. Transactions are secured using advanced cryptographic algorithms and private keys provide secure access control.[19]

2.1 | Smart contracts

The use of smart contracts, which are self-executing contracts with coded terms and conditions, is of great consequence in the utilization of blockchain technology to enhance efficiency and facilitate the development of robust domain-specific decentralized applications. These contracts operate on decentralized blockchain platforms, leveraging code to define, verify, and execute the terms of an agreement. In essence, smart contracts are distinguished by three key attributes: autonomy, transparency, and trustlessness. These characteristics ensure that contractual conditions are executed automatically when predefined criteria are met.[20,21] Smart contracts automate and enforce contractual obligations, providing stakeholders with a trustless and tamper-proof mechanism for executing agreements.[22] These contracts can automate payment disbursements, reduce reliance on intermediaries, track project milestones, and enforce compliance, thereby mitigating the risks of delays and disputes and optimizing project timelines and costs.[23]

2.2 | Hyperledger Fabric

Hyperledger is a major private distributed ledger technology (DLT) platform.[19,24] HLF, a key framework within Hyperledger, offers a modular, permissioned blockchain platform for enterprise applications. HLF's modular architecture allows the use of various data formats and consensus mechanisms.[25] Smart contracts (chaincodes) may be written in a variety of prominent, versatile programming languages, including Java and Go.[25,26] Transactions are processed through a series of endorsement, ordering, and validation phases, which enhance system scalability by allowing selective execution of chaincode and ensuring security through the imposition of identity and access management, as well as the implementation of safety algorithms to protect against faulty or compromised components.[25,26] HLF's distinguishing feature is managing multiple ledgers through private channels. These channels facilitate subgroup transactions, providing confidentiality in shared business networks.[26] In contrast to other DLT systems, HLF ensures transactions remain visible only to relevant participants, a crucial feature for competitive entities within the same network.[25,26]

3 | RESEARCH METHODOLOGY

Blockchain technology has gained prominence across various sectors due to its secure and inherent-proof nature. In the context of the construction industry, understanding its potential applications and impact is crucial.

To address the research question, a mixed-method research approach was utilized, synthesizing a systematic literature review and subsequent analysis of existing methods, possibilities, and limitations of blockchain integration within the construction industry to develop the proposed concepts.[27,28] While employing mixed-method research approaches can cause reliability issues if not done systematically,[29,30] such employment has a proven track record in investigating several construction-related themes, for example, Refs. 31–33.

The systematic literature review component employed a concept-centric methodology enhanced by units of analysis. This approach allowed recognition of the point of completion when no further relevant concepts emerged. The focus was on the lifecycle of construction fastening components and the properties of blockchain technology itself. Units of analysis naturally developed throughout the review, aiding its refinement through selecting suitable application examples. The references-of-references and snowballing methods were utilized to strengthen the systematic review and avoid a limited sample scope.[30] The primary search strings were "Blockchain AND Construction Industry" and "fastening AND blockchain," leading to several more refined units of analysis such as "fastening AND smart contracts" and "Product Lifecycle AND Blockchain OR Smart Contract." The literature review was conducted from 2021 to 2024, a timeframe chosen to capture the rapid advancements and increased maturity of blockchain technology within this period. Blockchain applications in the construction industry began gaining significant traction around 2021, marked by growing body of academic and industry-focused research addressing its integration into construction workflows and product lifecycles. By limiting the review to the most recent publications, we aimed to ensure that our analysis reflects the current state of the art and incorporates the latest developments in both blockchain technology and its application in the construction industry. The search spanned multiple academic databases including Google Scholar, Web of Science, and Scopus, and applied search terms to titles, abstracts, and main texts to identify relevant publications. A total of over 25 000 publications in the relevant field were identified. Using filters and exclusion criteria, relevant publications were subsequently selected for further analysis.[34] To analyze the existing methods, possibilities, and limitations of blockchain integration in the construction industry, specifically in prefabricated construction products and on the example of fastenings, the focus was placed on publications that provide an overview of the state of the art. Initially, general articles on the application possibilities in the construction industry were identified, followed by more specific articles in the area of product lifecycle.

In the subsequent phase, the identified publications were used to analyze and summarize existing methods, possibilities, and limitations of blockchain integration in the construction industry and the product lifecycle. Based on this analysis, we developed a conceptual framework using HLF, chosen for its modular architecture and ability to create private channels. Unlike public blockchains, which store data in a fully decentralized manner accessible to all network participants, HLF allows for the segmentation of data into private channels.[25,26] This enables controlled access to sensitive transaction data, addressing critical concerns about confidentiality and regulatory compliance in the construction industry. While public blockchains can also offer robust security mechanisms, they often face challenges such as handling large data volumes and maintaining privacy without compromising transparency. In contrast, HLF's architecture ensures scalability and selective data visibility tailored to multi-stakeholder environments, such as the fastening technology supply chain.

HLF also supports the application of general blockchain concepts, such as increased transparency, traceability, and the use of smart

TABLE 1 Summary of key concepts and applications of blockchain in construction.

References	Application	Findings and implications
39–44	BIM and CAD	• Improved data reliability and trust • Clear ownership and accountability • Uncertain legal validity
21,45–51	Contract management	• Automation and cost savings • Security and reliability • Improved payment processing
52–57	Project management	• Assistance in various management areas (contract, purchase, finance, subcontractor) • Provide an agile and decentralized approach to construction project management • Smart contracts can facilitate peer-to-peer collaboration
43,58–68	Supply chain management	• Enhance trust in supply chain management by providing protection mechanisms and shifting trust from relational to system-based • Improve payment settlements, compliance management, material planning, and the tracking and verification of items in real time through smart contracts • Holistic system view to address interconnected issues, such as collaboration, information sharing, and sustainability
43,68–70	Internet of Things (IoT)	• Ensures that the real-time updates from IoT devices to BIM are accurate and trustworthy • Provides a reliable and transparent method for managing the large amounts of data generated by IoT devices, ensuring that all stakeholders can trust the information being used • Control and management of the data become decentralized • Verify and add confidence to all data transfers within the IoT-enabled BIM system

contracts, across the entire lifecycle of a fastener. These capabilities enable the immutable recording of every transaction associated with a fastener, from manufacturing to disposal, providing a comprehensive audit trail. Smart contracts within HLF can specifically automate processes such as compliance verification, payment initiation, and real-time inventory updates, improving the efficiency, reliability, and accountability of supply chain operations. By leveraging these features, the proposed framework addresses the unique challenges of the construction industry, where secure data sharing and process automation across diverse stakeholders are critical.

Since the components of the (qualitative) systematic literature review and qualitative data analysis and the development of concepts belong to different research paradigms, metatriangulation inquiries were considered to ensure the consistency of the synthesis attempted through the mixed methods approach.[35,36]

4 | INDICATIVE EXAMPLES OF BLOCKCHAIN IN THE CONSTRUCTION INDUSTRY

The construction industry plays a key role in global productivity and economic growth. With major disruption coming from digital technologies such as artificial intelligence (AI), the Internet of Things (IoT), and building information modeling (BIM), blockchain is emerging as a promising solution. Blockchain can potentially impact the entire construction industry with its various players, procedures, and processes.[37,38] Table 1 provides an overview of established concepts and applications of blockchain in construction. The following section offers a comprehensive discussion of these concepts and applications.

4.1 | Building information modeling (BIM) and computer-aided design (CAD)

Blockchain technology is transforming BIM and CAD in construction, enhancing data transparency, traceability, and security while addressing industry inefficiencies.[39,40] By ensuring the immutability and authenticity of shared data,[41] blockchain fosters trust and collaboration across the supply chain. A key application in BIM is the automated management of building permits using smart contracts, which streamline the compliance verification process.[40,42] These smart contracts encode regulatory terms into computer-readable rules, enabling real-time validation of BIM data against these standards and significantly reducing human errors and bureaucratic delays. In the context of CAD, blockchain ensures that design modifications are securely logged and tracked, providing a reliable audit trail for project changes.[43,44] This capability is crucial for maintaining version control and accountability, particularly in large-scale projects where multiple stakeholders are involved. Furthermore, blockchain's potential in automated invoicing systems, when integrated with BIM and CAD, facilitates precise and timely payment processes, linking completed work directly to financial transactions.[43]

4.2 | Contract management and smart contracts

Smart contracts have revolutionized contract management in the construction industry by introducing automation, transparency, and efficiency. Deployed on blockchain platforms, they enforce contract terms without intermediaries,[45,46] addressing challenges like delays, disputes, and manual errors. Smart contracts enable real-time monitoring and execution of contract conditions, linking payments directly to project milestones.[47,48] This ensures prompt compensation for contractors upon task completion, reducing cash flow issues and improving financial predictability. The immutable nature of blockchain safeguards contracts against fraud and disputes.[21,49] In construction, smart contracts are particularly effective in managing subcontractors and suppliers by automating procurement, from tendering to delivery and compliance verification. This automation streamlines operations, reduces administrative overhead, and ensures that all transactions are transparent and traceable.[49,50] Moreover, the integration of smart contracts with Building Information Modeling (BIM) systems further enhances contract management by providing a single, unified platform for tracking project progress and contractual obligations.[21,49,51] This synergy allows for precise alignment between physical and digital aspects of construction projects, ensuring that all stakeholders have access to accurate and up-to-date information.

4.3 | Project management

The integration of blockchain technology into project management within the construction industry marks a transformative shift, offering enhanced transparency, efficiency, and collaboration. Blockchain's decentralized ledger system provides a secure, immutable record of all project activities, ensuring transparent and accessible data for all stakeholders.[52,53] This technology addresses longstanding issues in project management, such as data silos, miscommunication, and lack of accountability. One of the most significant benefits of blockchain in project management is its ability to improve trust among participants by recording every transaction and update on a tamper-proof ledger, ensuring all parties have access to the same information in real time.[54] This transparency fosters collaboration and reduces disputes. Additionally, blockchain enhances the traceability and accountability of project activities by creating a comprehensive audit trail of every action and decision made. This capability is crucial in complex construction projects, enabling project managers to track progress, ensure compliance, and mitigate risks with real-time, verifiable data.[55–57]

4.4 | Supply chain management (SCM)

The implementation of blockchain technology in supply chain management (SCM) within the construction industry represents a significant advancement, offering enhanced transparency, traceability, and efficiency. Blockchain's decentralized and immutable ledger system securely records all transactions and data exchanges, making them accessible to all stakeholders in real time.[58–60] This capability addresses critical issues such as fraud, inefficiency, and lack of trust that have historically plagued construction supply chains.[61] One of the primary benefits of blockchain in SCM is the enhanced transparency it provides. Every transaction, from the procurement of materials to their delivery on-site, is recorded on a tamper-proof ledger.[58,62] This transparency allows all participants, including suppliers, contractors, and project managers, to have a clear view of the supply chain processes. It reduces the risk of fraud and errors, ensuring that all parties have confidence in the accuracy of the information.[63] Traceability is another significant advantage offered by blockchain technology in SCM. By enabling the tracking of materials and components from their origin to their final destination, blockchain ensures that any issues related to quality or compliance can be quickly identified and addressed.[58,64–66] This traceability is particularly valuable in ensuring that materials meet the required standards and specifications, thereby enhancing the overall quality of construction projects. Blockchain also optimizes logistics and operational efficiency within the supply chain. Smart contracts, which automate the execution of contract terms when predefined conditions are met, streamline processes such as payments, order fulfillment, and compliance verification.[67,68] This automation reduces administrative overhead, speeds up transactions, and minimizes delays, leading to more efficient and reliable supply chain operations.

4.5 | Internet of Things

The integration of blockchain with the Internet of Things (IoT) in construction enhances data security, transparency, and efficiency. IoT devices, equipped with sensors, collect real-time data on construction activities and environmental conditions.[43,69] Blockchain ensures this data is securely recorded and immutable, fostering trust among stakeholders. This combination enables precise tracking of materials, improves compliance with regulations, and optimizes resource management.[70] Smart contracts further automate processes, such as payment triggers and supply chain logistics, based on real-time IoT data.[43,69]

5 | CONCEPT AND IMPLEMENTATION OF HLF IN FASTENING TECHNOLOGY

This chapter presents the conceptual development and practical implementation of HLF (HLF) within the field of fastening technology. The product lifecycle of fastening components serves as the analytical framework to explore the technical and industrial characteristics of these products while identifying opportunities for digital enhancements through HLF. The focus lies on how HLF can enhance transparency, traceability, and efficiency across the entire value chain—from material procurement and production to certification, installation, and recycling. In this context, the chapter examines the various stages of the product lifecycle, providing a comprehensive foundation for analysis and optimization.

5.1 | Product life cycle in fastening technology as an investigation framework

The life cycle of a construction product encompasses a series of stages,[70] spanning across the material sourcing and manufacture, the installation and use, and the final decommissioning stage, according to cradle-to-grave or cradle-to-cradle concepts (i.e., linear resource use, ending as waste, or circular design, enabling continual recycling or reuse without producing waste, respectively). By delineating these stages, a comprehensive understanding of fastening technology's technical and industrial features is established, and digital enhancement pathways through HLF are explored. The life cycle of a construction product is a complex process that involves several stages, yet classifying its various stages allows for standard frameworks to examine it.[3,70,71] The initial step in the life cycle of a post-installed fastener is the sourcing and procurement of raw materials from various sources and transportation to a manufacturing unit. Manufacturing involves producing various components comprising a fastener within a single or several geographically spread factories. Assembling and packaging are then carried out at a single location as the first step of the market supply chain. This encompasses the transfer of post-installed fasteners from the manufacturer to the point of installation, yet with one or more intermediate storage intervals in warehouses or distribution centers. Proper storage conditions, such as temperature control and protection from moisture, are crucial to maintaining the integrity of the fasteners. In parallel to the production runs, production quality control and assurance and certification are essential parts of ensuring the safety of installed fastenings in practice. Certification bodies evaluate the manufacturer's quality control procedures and product performance. In the design and construction/assembly stage, the responsible engineers specify fastening products, and these have to be installed on-site to connect and assemble various further components. Installation requires tools corresponding to the product and a predefined work methodology, for example, with predefined work steps per the manufacturer's and engineer's instructions. Installation quality is also vital in this step and can be enhanced through trained labor and site supervision, while in some cases, on-site testing is required to provide confidence in the as-built performance. During use, fastenings must withstand various loads and environmental conditions. Regular inspections and maintenance are essential to ensure the fasteners' structural integrity and prevent premature failure. When post-installed fasteners reach the end of their service life, they can be recycled or reused to reduce the environmental impact of construction waste and conserve resources. The recycling process involves dismantling the fasteners, separating the different materials, and processing them into reusable forms. At the same time, reuse should entail a confirmation of the product's remaining service life and suitability. Four main industry sector categorizations can be distinguished in parallel to the established life cycle stages. This involves organizing the stages into four key categories: (i) material resources, (ii) quality assurance and design, (iii) supply chain, and (iv) installation and use. In order to conceptualize implementations of an HFL for fastenings, a standard classification according to a typical building

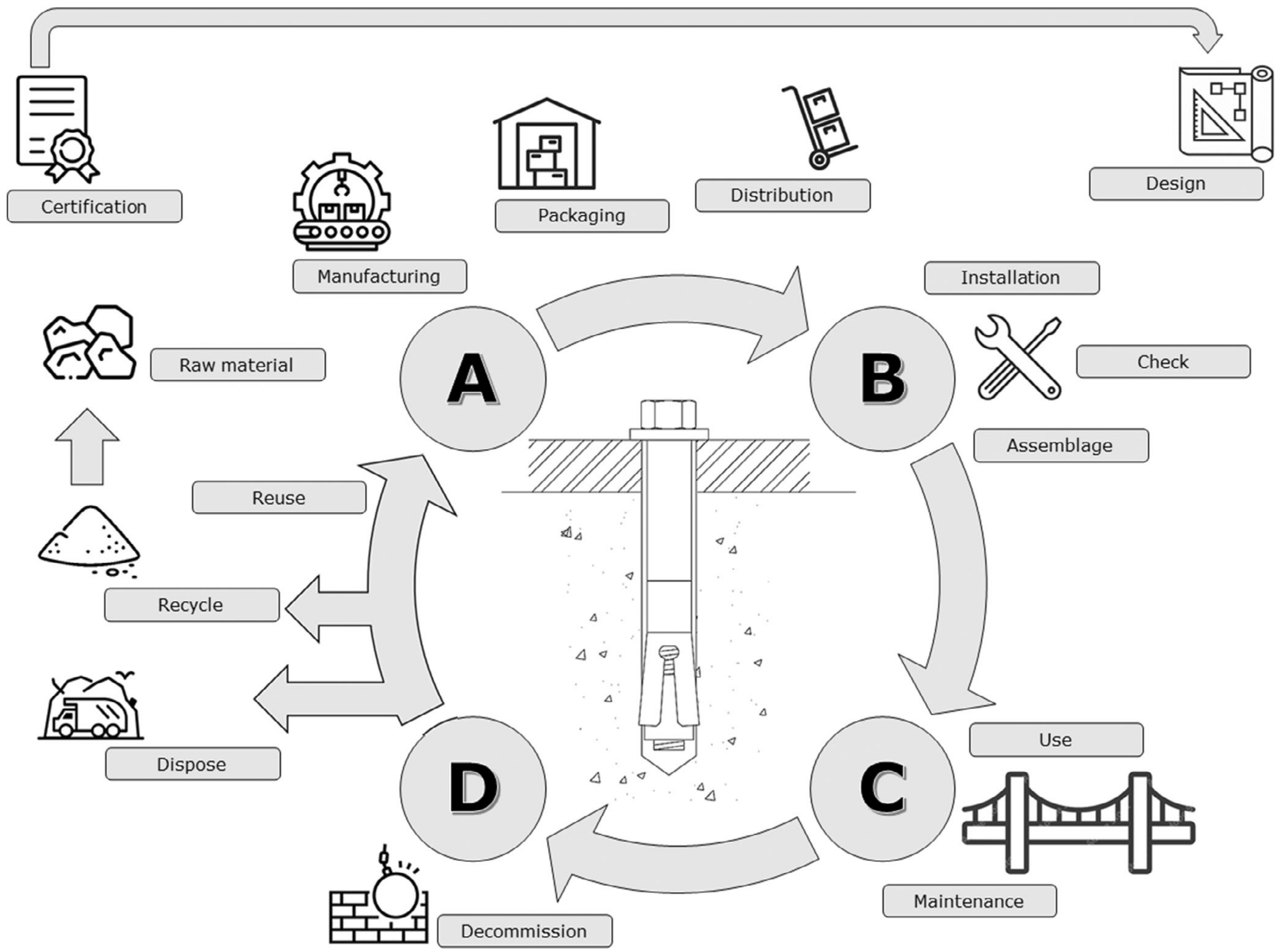

FIGURE 1 Graphical representation of a fastening product's life cycle.

life-cycle assessment[70] is adopted for the post-installed fastening application and presented in Figure 1, whereby the four main pylons of investigation escorting the typical life cycle are highlighted.

5.2 | Implementation possibilities of HLF technology

Based on the investigation approach and the lifecycle conceptualization mentioned above, it is attempted to detail the conventional processes, participants, and information involved at each stage in relation to how HLF can be integrated and digitally enhance this procedure from raw material sourcing to recycling and reuse.

5.2.1 | Material procurement, product fabrication, and recycling

In the conventional approach to fastener production, the journey of a fastener from raw material to finished product is marked by a series of data exchanges. Basic raw materials are derived from recycling scrap metals or from sintered mined ores,[72,73] characterized by chemical and physical variations for each extraction batch, which may influence production efficiency and the final product's mechanical properties.[73] Further process steps include deoxidation of iron ores in direct or blast furnaces, decarburation, electric arc melting for scrap, casting and rolling, and any associated transportation activities.[73] The resulting steel coil or wire drums are fundamental components of fastener production. The vast majority of environmental impacts of the product's lifecycle are attributed to these production steps. The fastener undergoes predominantly cold-forming steps (such as cutting, upsetting, deburring, calibration, and threading), quality checks, and packaging.

Recycling construction products holds immense importance for both environmental and economic reasons. By diverting construction waste from landfills, valuable resources are conserved while greenhouse gas emissions and pollution are reduced.[74,75] Recycling often produces materials at a lower cost than new production, benefiting construction budgets. Throughout this intricate process, information about the fastener's material origin, properties, production parameters, and quality certifications is meticulously documented and conveyed between the various stakeholders.[69,75–77] However, this traditional information management method is susceptible to human errors, data discrepancies, and a lack of transparency.

HLF can introduce a paradigm shift in fastener production by establishing a secure and tamper-proof digital ledger to store and manage all relevant information.[78,79] This transformative approach eliminates the need for manual data entry and reconciliation, fostering greater efficiency and accuracy.[80,81] By leveraging HLF, the entire fastener production process from steel wire sourcing to final product delivery can be effectively tracked and traced. Material properties, manufacturing parameters, quality inspection reports, and delivery details are securely stored on the blockchain, providing a transparent and verifiable record of the fastener's journey. HLF's permissioned architecture, modular design, and privacy features enable secure, efficient data management and traceability in fastener production. These capabilities offer customized solutions to integrate seamlessly with existing systems while ensuring scalability, data confidentiality, and streamlined monitoring across the material procurement, product fabrication and recycling phase, and also the whole production lifecycle. This enhanced traceability enables manufacturers to identify and rectify potential issues swiftly, ensuring the delivery of high-quality fasteners to their customers.

5.2.2 | Certification and engineering design

The certification of fastenings, particularly for safety-critical applications, is primarily based on a certified "European Technical Product Specification" (ETPS) for each fastening product in accordance with the Construction Products Regulation (CPR).[82] This introduces standards for the paper-based and digital CE certification of fastening products and the specification duties of construction project stakeholders.[82,83] The CPR pronounces seven basic requirements to be addressed in ETPS: (i) mechanical resistance and stability; (ii) safety in case of fire; (iii) hygiene, health, and the environment; (iv) safety and accessibility in use; (v) protection against noise; (vi) energy economy and heat retention; and (vii) sustainable use of natural resources. The structural performance is at the forefront,[84,85] while products intended for the installation of thermal insulation panels come with adaptations of non-metallic parts to prohibit thermal bridges and potentially noise transfer. Essentially, the ETPSs deliver information about the fabrication, installation, and associated performance of each product under certain conditions (e.g., strength and cracking of concrete, fire or seismic actions). For concrete fastening products, the ETPS is the "European Technical Assessment" (ETA), prepared on the basis of a "European Assessment Document" (EAD).[86] Another option is that the ETPS is a harmonized European standard (hEN); this may be the case for construction adhesives or rebar anchorages, not for fasteners. The "European Organization for Technical Assessment" (EOTA) drives this standardization procedure by endorsing and publishing the assessment principles and by coordinating the organizations carrying out the assessment ("Technical Assessment Bodies").

An increasingly significant specification also enforced by the CPR relates to the product's environmental impact in its Environmental Product Declaration (EPD). Common Product Category Rules (PCR), that is, guidance for EPD development, are outlined for the construction sector in Europe by EN 15804.[87,88] The proposed revision of the CPR provides the regulatory framework for the digitalization of construction product specifications based on a "Digital Product Passport" (DPP).[89]

The architectural and structural design depends on the building and fitout project's geometrical and structural requirements. The structural design for fastenings establishes the system's safe load bearing. It relies largely on established codes and standards and, for less typical details, on industry guidance documents as well as permits and case approvals of customized engineering solutions. Design drawings and documentation must include information about the specific product and its use conditions, as well as setting location and installation tolerances. The implementation of BIM belongs to this lifecycle phase, and collecting as much information as reasonably achievable in such models is beneficial during the entire product and asset lifecycle. Information included for fastenings can be ordered by Level of Development (LOD) from generic objects with approximate volumes or geometries up to a fully detailed dataset of the fastening product including locations, dimensions, technical specifications, installation date and service life, subcontract, and procurement information, as well as material and project condition information.

For HLF integration in the area of certification and approval, the testing institutions and approval bodies must participate in the blockchain platform. This way, a well-defined channel should be established between manufacturers, approval bodies, and testing institutions.[90] Manufacturers submit information about their product to a certifying organization, which considers the independent evaluation of the testing institution and, if compliant with the safety, quality, and environmental requirements, issues an approval notice outlining specific conditions for its use and marking. Data could be exchanged here securely, quickly, and transparently via predefined roles and access rights to make the authorization process more efficient.[91,92] The proposed streamlined process (Figure 2) makes ensuring safe and compliant construction products more efficient. Manufacturers initiate the journey by submitting their applications and product information to authorities through a central data exchange platform, facilitating the flow of information throughout the process. The authority retrieves the information, develops a test plan based on EU CPR requirements, and seamlessly uploads it back to the hub. Manufacturers can then select testing institutions, share product samples, invite them to the platform, and grant them access to relevant documents. Equipped with the test plan and product, these institutions conduct their evaluations and upload their test reports to the hub, automatically notifying the authority upon completion. Once the authority reviews and accepts the reports, they upload the construction product certificate signifying approval and directly inform the manufacturer. Manufacturers then hold the power to share this crucial approval notice with their customers (project stakeholders) through a public link, which is easily accessible via a digital tag placed directly on the product itself (e.g., QR code, NFC, RFID). This collaborative approach, leveraging a central platform for seamless information exchange, fosters

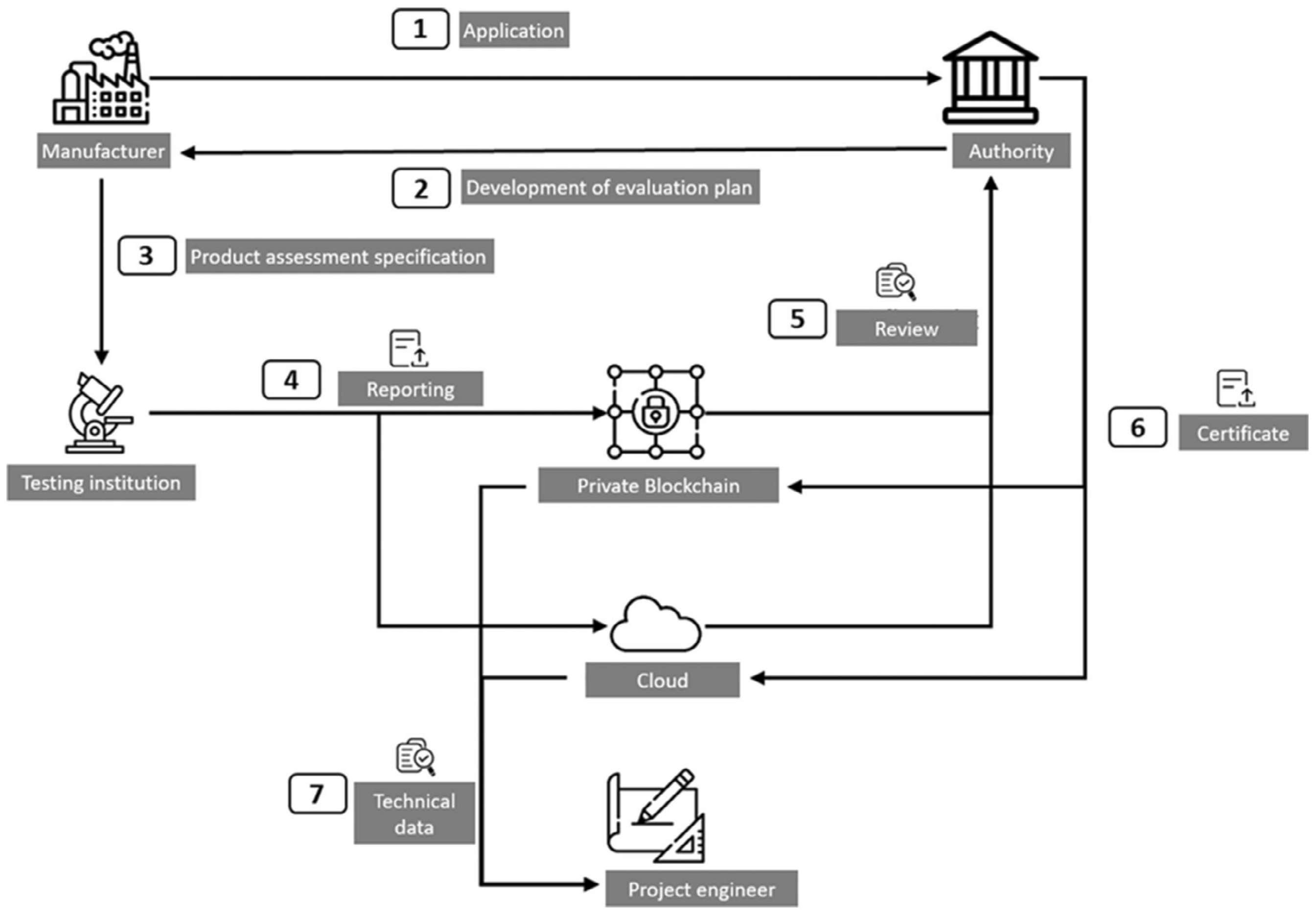

FIGURE 2 Schematic representation of the HFL-based certification process in the construction products context.

transparency and security while it streamlines product approval for both manufacturers and regulatory bodies, ultimately contributing to safer and more compliant construction materials.[90,93] By transferring the technical data into a BIM-based fastening design, a secure, transparent, and immutable record of approvals and design interfaces but also of design modifications can be maintained.[91,94] This integration facilitates data integrity and accountability among all stakeholders, particularly for industrialized products and processes.[87,95,96] Efficient collaboration is ensured by reducing errors and miscommunication during the construction process and by intellectual property protection.

5.2.3 | Supply chain

The construction sector relies on a complex network of suppliers, manufacturers, and logistics providers to deliver materials, equipment, and labor to project sites. Traditional processes involve paper-based procedures, siloed information, and limited visibility across the chain.[97,98] Chronic malfunctions of supply chains in construction and other industries have been related to price volatility and the availability of fuel, as well as geopolitical crises, conflicts, and piracy. While these persist, modern challenges attributed to synchronization and interface management in the global market and the worldwide shortage of skilled workforce across construction and logistics further complicate construction products' delivery and call for a more resilient and efficient approach.[99–103] In fastening technology, aspects of specific interest relate to the quality of interim storage and transport conditions, particularly for the more susceptible synthetic materials, and the dual supply modes that can be found in this sector, that is, direct retail to end users and wholesale by intermediate distributors and hardware stores.[97,104] Here, one should consider that the fastenings sector in the construction industry is dedicated to building flexibility and innovation, which leads to significantly large numbers and constant evolution of codes in manufacturers and distributors' catalogs, which require sophisticated logistics systems.

HLF has been developed and is widely implemented to regulate the integrations and interfaces between different organizations in enterprise applications as is the case with the conveyance of products from the manufacturer to the end user.[105–107] It presents an enhanced pathway for improving fastening product delivery performance within the construction industry's complex supply chains. The technology offers enhanced visibility through a shared, tamper-proof record of each product's journey, streamlining documentation with smart contracts and optimizing inventory management with real-time data. Additionally, linked sensors embedded in the product or the packaging can independently track the location as well as the environmental conditions for sensitive materials.[108] Moreover, such a system can be integrated with off-site construction and lean-managed projects where the timing of supply is a key agent for project performance. In order to overcome challenges regarding data privacy and regulatory compliance, the inviolable nature of HLF can observe legislations[109]—steps are also being undertaken at the European regulatory level.[110,111]

5.2.4 | Installation and technical performance quality

An important aspect of the technological development of fastening products is the facilitation of safe installation because installation defects can substantially decrease the fastening's structural performance.[8,112] This is critical for bonded anchors,[113,114] while it is also evident by the fact that increased resistance partial safety factors are recommended for anchorages with potentially low installation quality.[85] Before using a fastening element on the construction site, fitters must carefully review the manufacturer's specifications, approval certificates, and any relevant design documents. Ensuring the quality and soundness of anchor installation requires consideration of numerous factors, including the anchor's suitability, approval validity, proper packaging/storage, and the use of appropriate tools and techniques.[86,115,116] Supervision plays a crucial role in verifying these elements and maintaining long-term installation records. However, the current process, with its reliance on paper-based documentation and manual supervision, presents challenges. These include the potential for human error in data transfer, time-consuming verification, and the risks inherent in managing physical records over extended periods. These limitations highlight the need to explore ways to optimize anchor selection, installation practices, and record-keeping to ensure structural integrity. Here, integrated sensors for mechanical monitoring data can also offer additional quality assurance based on digital records.[114,117–120]

HLF offers a promising solution to address the limitations of the current system. By creating a secure distributed ledger network, HLF can establish a single source of truth for all anchor-related data. Manufacturer specifications, approval certificates, and installation details can be immutably recorded on the ledger, ensuring all participants have access to the most up-to-date and verifiable information.[43,121,122] Smart contracts could be deployed to automate quality checks, verifying anchor suitability based on predefined parameters and ensuring installation procedures adhere to specifications.[121–124] Furthermore, the tamper-proof nature of the ledger would eliminate concerns about document manipulation and facilitate efficient recordkeeping. Real-time access to installation data would enhance supervisory oversight, streamline the audit process, and release project progress and delivery milestones.[121,125] Additionally, as the construction industry embraces digital planning, modular offsite construction, and AI-supported and robotic installations, integrating anchor data within an HLF network would become essential.[126–128] This integration could enable real-time quality control during prefabrication, automated verification during robotic installation, and a permanent digital record for future maintenance and traceability. Regarding sensor integration for lifecycle quality, HLF technologies would equally ensure the integrity of the data, enhancing trust among stakeholders and facilitating long-term analysis of structural performance. Smart contracts could be employed to automate condition assessments based on predefined thresholds, triggering alerts or maintenance interventions. Additionally, HLF could streamline data sharing between designers, manufacturers, installers, and asset managers, providing a collaborative platform for understanding overall structural health while confirming the product or its material condition with regard to reuse and recycling.

6 | DISCUSSION

6.1 | Findings and recommendations

The implementation of HLF technology presents a significant opportunity for a revolutionary transformation of the fastening industry's operational processes across various stages of the product lifecycle. One of the principle advantages of adopting HLF is its potential to enhance transparency and traceability throughout the fastening lifecycle. By securely recording and managing data related to material sourcing, manufacturing processes, quality control measures, and certification procedures on a distributed ledger, stakeholders can access real-time information and verify the authenticity of product information. This heightened transparency not only fosters trust among stakeholders but also enables the swift identification and resolution of issues, thereby improving overall product quality and safety.

Furthermore, HLF has the potential to streamline certification processes by automating quality checks and facilitating seamless information exchange between manufacturers, approval bodies, and testing institutions. This digitalization of certification procedures not only accelerates the approval process but also reduces administrative burdens and minimizes the risk of human error. The integration of smart contracts into HLF networks allows for the automation of various contractual obligations, reducing reliance on intermediaries, accelerating processes, and mitigating the risk of disputes. The efficiency gains from such automation can lead to significant cost savings and improved project timelines, ultimately benefiting the entire construction supply chain.

Moreover, the choice of HLF as the foundational technology is rooted in its ability to address key challenges that traditional systems and competing technologies (such as BIM and conventional software solutions) cannot adequately resolve. Specifically, HLF combines the robustness of distributed ledger technology with modular and permissioned architectures. This allows it to provide transparency and traceability while maintaining privacy and compliance with data protection regulations—a critical requirement in the fastening industry where sensitive proprietary information and compliance standards coexist.

Unlike fully public blockchain systems, HLF enables fine-grained control over who can access what data. This ensures that stakeholders can trust the system without compromising confidentiality, particularly in multi-party collaborations where trust and transparency are pivotal. The integration of smart contracts further differentiates HLF, enabling automated enforcement of certification criteria, streamlining inter-party agreements, and significantly reducing administrative overhead and the risk of disputes.

By reiterating these benefits, it becomes evident that HLF not only aligns with but actively addresses the specific needs of the fastening industry, providing a solution that is tailored to its lifecycle challenges.

However, the implementation of HLF also poses a number of challenges. One of the primary concerns is the protection of data privacy and adherence to regulatory compliance, particularly with regard to the sharing of sensitive information across multiple stakeholders. The resolution of these concerns necessitates the implementation of robust data protection measures and strict adherence to regulatory requirements, which may vary across different jurisdictions. Ensuring that all participants in the HLF network comply with these regulations is critical to maintaining the integrity and trustworthiness of the system. Additionally, the technical complexity of implementing and maintaining a blockchain-based system can be a barrier for some organizations, particularly smaller firms with limited IT resources.

Furthermore, the successful implementation of HLF relies on widespread adoption and collaboration among industry stakeholders. Overcoming resistance to change and fostering a culture of innovation will be crucial in driving the adoption of blockchain technology across the fastening industry. Stakeholders must be willing to invest in the necessary infrastructure and training to fully leverage the benefits of HLF. This entails developing a comprehensive understanding of blockchain technology and its applications, as well as establishing clear guidelines and best practices for its utilization. Collaboration among industry leaders, policymakers, and technology providers will be essential to creating an ecosystem that supports the widespread adoption of HLF.

In conclusion, our analysis demonstrates that HLF has the potential to transform the fastening industry's operations in significant ways. These include enhancing transparency, streamlining certification procedures, and improving overall efficiency. Although challenges remain, the benefits of blockchain integration outweigh the obstacles, paving the way for a more transparent, efficient, and sustainable fastening ecosystem.

The topic of blockchain continues to be present in the media and is represented in academic publications primarily by consideration of cryptocurrencies and Bitcoin. This article attempts to provide an approach that goes far beyond the usability of cryptocurrencies, highlighting the practical applications of blockchain in the fastening industry. The use cases demonstrate blockchain's potential to enhance certification authenticity, supply chain transparency, and automate contracts, but emphasize the need for careful assessment against existing technologies (e.g., BIM and conventional software solutions), which may as well render a blockchain application superfluous.

Moreover, while blockchain technology offers a multitude of advantages, it is not without limitations. The lack of easily configurable, user-friendly, and comprehensive blockchain products remains a significant barrier to adoption. Additionally, the necessity for standardization and regulatory frameworks to govern the utilization of blockchain in the construction industry is critical. Addressing these issues will require ongoing research and development, as well as collaboration among industry stakeholders to establish common standards and best practices.

It is also important to consider the social and organizational factors involved in the adoption of blockchain technology. The implementation of new business processes and models will probably result in the emergence of novel collaborative arrangements among participants in the supply chain and possibly also among competitors. This type of transition requires adjustments in mindset beyond the technological aspects. Establishing trust in a new technology that has not yet been extensively tested is a significant challenge. Furthermore, a considerable number of organizations have yet to undergo a comprehensive digital transformation, which presents an additional obstacle to the implementation of blockchain systems. The step of digitization represents a barrier to many companies and the adoption of blockchain technology. However, it also presents an opportunity to integrate blockchain systems into the infrastructure as part of the digitization process.

In particular, the ability to seamlessly integrate blockchain systems into existing networks and adapt them to existing business processes is likely to be a crucial aspect of the acceptance of blockchain systems. Organizations are often reluctant to disclose their data and processes and share them with all other network participants due to the transparency of a blockchain. Consequently, they are more likely to utilize blockchain systems where privacy can be assured. The viability of employing a blockchain platform hinges primarily on the particular objectives of the application. It is advisable to implement blockchain where a corresponding centralized approach would prove to be significantly more complex or where centralized options are lacking.

The discussion highlights the transformative potential of HLF technology for the fastening industry, emphasizing both the opportunities and challenges associated with its implementation. By meticulously considering these factors and fostering a collaborative approach, the industry can leverage blockchain technology to drive innovation, efficiency, and sustainability in fastening technology and beyond.

6.2 | Conclusion and future work

This paper has examined the potential implications of integrating HLF technology into the fastening industry's operations. Through a comprehensive analysis of the fastening lifecycle, we have identified opportunities for leveraging blockchain technology to enhance transparency, streamline certification processes, and improve overall efficiency.

The analysis begins by delineating the various stages of the fastening lifecycle from material sourcing and manufacturing to installation and end-of-life recycling. By mapping out these stages, we establish a foundational understanding of the complex processes involved in the production and utilization of fastening products.

Building upon this understanding, we explore the implementation possibilities of HLF technology within each stage of the fastening lifecycle. We discuss how blockchain integration can improve transparency, traceability, and certification procedures, thereby enhancing product quality and safety.

However, the adoption of HLF also presents challenges, including data privacy concerns and the need for widespread industry collaboration. Addressing these challenges requires robust data protection measures, regulatory compliance, and a commitment to fostering a culture of innovation.

In conclusion, our analysis demonstrates the potential of HLF to transform the fastening industry's operations. By embracing blockchain technology, stakeholders can unlock new opportunities for efficiency, transparency, and sustainability, ultimately driving positive change across the fastening ecosystem.

Future work could focus on developing more user-friendly and configurable blockchain products, establishing standardized regulations and solutions, and exploring additional use cases beyond the product lifecycle. Additionally, fostering collaboration among industry stakeholders and addressing social and organizational barriers to adoption will be crucial in realizing the full potential of blockchain technology in the construction industry.

AUTHORS CONTRIBUTION

Aileen Pfeil: Coordination and Conceptualization, Methodology. Writing - draft, review and editing, Dimosthenis Kifokeris: Methodology, Writing - review and editing Panagiotis Spyridis: Conceptualization, Methodology. Writing - draft, review and editing.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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