Blockchain Technology Accelerating Industry 4.0

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Abstract Competitive industrial environments impose significant requirements on data sharing as well as the accountability and verifiability of related processes. Here, blockchain technology emerges as a possible driver that satisfies demands even in settings with mutually distrustful stakeholders. We identify significant benefits achieved by blockchain technology for Industry 4.0, but also point out challenges and corresponding design options when applying blockchain technology in the industrial domain. Furthermore, we survey diverse industrial sectors to shed light on the current intersection between blockchain technology and industry, which provides the foundation for ongoing as well as upcoming research. As industrial blockchain applications are still in their infancy, we expect that new designs and concepts will develop gradually, creating both supporting tools and groundbreaking innovations.

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1 Introduction

The advances of the Internet of Things (IoT) and Industrial IoT (IIoT) fostered the development of cheap, long-living, potentially mobile sensors. These sensors lay the foundation for a pervasive gathering of data on workpieces, monitoring of production processes, and tracking of supply chains [107]. More specifically, the application of IIoT functionality, to make sensor data and aggregated information available to stakeholders in the Industry 4.0, promises improved product qualities [97], reduced overall costs [54], sustainable production [99], adjusted maintenance periods [95], optimized production planning [39], or more efficient resource usage [19].

However, making full use of sensor data often requires various stakeholders to combine their data and form an *Internet of Production* (IoP) [18, 94]. Thereby, companies may have to exchange data with yet unknown—and thus untrusted—collaborators, customers, or even direct competitors. Traditional IoT and IIoT security mostly focus on encryption and authentication to protect data in transit [57, 58, 60, 61, 120] or realize secure offloading to cloud resources [22, 34, 109]. When sharing data among mutually distrusting stakeholders, additional demands such as *verifiable correctness* and *immutability* of stored data emerge. Blockchain technology promises to provide corresponding security features for IIoT data handling in various industry domains and, thus, Industry 4.0. Specifically, the immutability properties of blockchains offer verifiability and accountability even in the face of mutually distrustful stakeholders. Furthermore, blockchain technology can build and represent a commonly agreed consensus among these otherwise mutually distrustful and conservative stakeholders.

Moreover, blockchain technology can be used in various configurations to adapt to the different industrial use cases. A common expectation is that the sharing of raw data or already analyzed and aggregated information will foster the move to more *dynamic* (business) relationships—even in competitive environments [93]—as trustworthy data can replace or bootstrap not yet existing trust in new collaborators. The accompanying benefits, such as better utilization of machine capacity, reduced costs, and flexible re-assignment in case of machine failures or transportation delays, mainly materialize *along* a supply chain (cf. CROSS-CHAPTER-REF:SupplyChains). Further improvements can be achieved if information is also shared *across* supply chains [95]. E.g., information on machine configurations, machine failure rates, or influence of environmental settings on production quality can greatly improve productivity for all users of a machine type globally. However, especially this scenario requires sharing of information between companies without any existing (trust) relationships [99]. This data sharing can have severe consequences if business secrets are leaked or misbehaving entities share falsified information, e.g., machine settings that reduce productivity or even cause damage to production lines or humans [54].

Blockchain technology provides various options to tailor its features to specific industry needs. For example, the uniqueness of a product can be modeled with blockchain technology to prevent double-spending. Similarly, blockchains can also support the use of pseudonyms for participants to hide their identities. Furthermore, different blockchain types provide a varying level of openness (i.e., public vs. private blockchain), trust (i.e., permissionless vs. permissioned blockchain), scalability (from massive amounts of raw data up to highly compressed aggregated information), and additional functionality (e.g., smart contracts). Consequently, blockchain technology can dynamically adapt to various industrial scenarios and their needs.

However, while the foundations of blockchain technology are well understood, research to integrate it into different industrial use cases is still in its infancy as novel—both challenging and interesting—use cases are still being proposed, researched, and implemented. Some initial approaches for industrial collaboration and data sharing surfaced recently but are mostly realized without blockchain technology, e.g., a mechanism for the exchange of production process parameters [98] or a remote knowledge system for a privacy-preserving data exchange [25]. These approaches lack the industry-demanded accountability and verifiability features or fail to incorporate different stakeholders altogether. Nevertheless, these initial approaches pave the way for more sophisticated realizations by underlining the unrealized potential.

We expect that the (full) utilization of blockchain benefits in industry, and especially in settings with multiple stakeholders, will follow a three-step pattern [95, 99] with an additional preparative step: **(0)** As a preliminary and preparatory step, expertise concerning blockchain technology must be established in the respective (industrial) domain, and decision-makers, engineers, and technologists need to be educated in the potential benefits of blockchain technology as well as in the handling of blockchain-supported technology and machines [2, 20]. **(1)** Afterward, existing use cases need to be remodeled and overhauled, improving existing (imperfect) approaches by integrating blockchain technology. **(2)** Following, these use cases have to be extended to also integrate market players without established trust relationships, superseding traditional trust with verifiable, trustworthy data. This step demands that the foundations of the novel technology are well understood and field-tested. **(3)** Finally, various new use cases will emerge and cover both trusted and untrusted entities by linking and connecting them using blockchain technology to unlock new potentials. Along this line, we present envisioned benefits achieved by the application of blockchain technology to Industry 4.0. However, we also shed light on the challenges when integrating this technology into the industrial domain and provide an overview of available configuration and design options to tackle these challenges. Furthermore, we outline the use of blockchains in early-adopting industrial domains.

Organization. This chapter is structured as follows. In Sect. 2, we give a broad overview of the potential of blockchain technology for Industry 4.0 by highlighting its envisioned benefits for industry in general. Afterward, in Sect. 3, we examine challenges and corresponding design options for integrating blockchain technology in Industry 4.0 use cases. Then, in Sect. 4, we identify domain-specific needs and potentials by surveying approaches across a variety of industrial sectors. Based on these analyses, we discuss our findings in Sect. 5, and conclude the chapter in Sect. 6.

2 Envisioned Benefits of Blockchain Technology in the Industry

The unique properties of blockchains, especially providing transparency, verifiability, and accountability in decentralized settings, i.e., where no central entity can take on a leading role, render their use attractive for various business and industrial use cases. Stakeholders hope for simplified processes and relationships [117], cost reductions [117], improved customer satisfaction and reputation [76], and greater independence from third parties [117]. In this section, we provide an overview of the benefits of blockchain technology for industries. As we will detail in Sects. 4 and 5, some of these benefits are of primary interest for specific industries, whereas others are relevant for many industrial use cases.

2.1 Increased Transparency (⊞I)

Blockchain technology promises to provide transparency for currently opaque processes. Bitcoin [85]—the first blockchain application—promotes the vision to make all information publicly available and enables access by everyone. This paradigm seems to stand in stark contrast to typical goals of the industrial domain, where full transparency is often infeasible. Specifically, businesses risk their competitive advantage when providing insight into business secrets, processes, and collaborations; public access to such data could further hinder competition and even stall innovation. Consequently, stakeholders often lean towards keeping as much information secret as possible [43]. Nevertheless, as we explore next, industries can benefit from increased transparency by integrating blockchain technology into their processes.

2.1.1 Business-to-Business Transparency

Sharing information about (i) the origin of products, (ii) production details, and (iii) product destinations along the supply chain can yield benefits for businesses [97]. Specifically, businesses with access to public and immutable assurances of production steps along the supply chain can guarantee product properties without becoming liable for false claims by predecessors in the supply chain. In case of disputes, the liable entity can be unambiguously identified by all involved entities.

Despite these benefits, businesses often cannot afford to share the required detailed information about their production steps. Nevertheless, already the sharing of partial information, e.g., the product's origin, can result in advantages for the involved entities. More and more businesses desire to track the origin and trade intermediates of base products for legal, ethical, or marketing reasons. This information enables businesses to ensure the sustainable and legal sourcing of raw material [33, 65] and to unveil criminal associations or corrupt entities among their suppliers [112]. Likewise, the immutability and transparency properties of blockchains provide up-to-date tracing data and information on past actions, which can increase the credibility of businesses [65]. E.g., access to trustworthy immutable data enables businesses to detect conflicting information and tempered claims early on [15, 74].

Considering legal frameworks, public access to business processes has the potential to realize a fair market access for each competitor by ensuring that every entity is abiding by the law. To this end, the ability to follow processes makes it harder to evade detection when breaking laws. Specifically, public records enable law enforcement, regulatory authorities, and competitors to check the compliance of business actions with the laws. Notably, digitalization would also allow businesses themselves to review and audit their actions to prevent misbehavior in the first place.

2.1.2 Business-to-Customer Transparency

Consumers become concerned about the ethics and sustainability of products, and consequently, they demand assurance that what they buy does not negatively impact others or the environment [28, 86, 121]. Research even repeatedly showed that the consumers' likelihood of purchasing "greener" products depends on how confident they are that a product is really green [48, 92]. Similarly, customers and companies are concerned about buying products that support terrorists, criminal associations, or corrupt entities [112]. Using blockchains to establish transparency on how the material is sourced, processed, sold, and maintained helps customers to select suitable products. E.g., transparent sourcing promises to prevent blood diamond trades [36] or illegal tuna fishing [118].

Furthermore, customers benefit from access to historical price information, (business) behavior, sustainability, and contract conditions. They can then base purchase decisions on, e.g., worker conditions or fair trading agreements. Businesses that can reliably and credibly provide corresponding data through blockchain technology become more attractive to customers, which boosts the businesses' revenue and reputation [65]. Thereby, blockchains enable customers to choose based on unbiased data of long historical periods and without relying on a trusted third party.

Transparent processes also enhance business relationships that comprise a direct feedback loop between customers and company, e.g., continuous maintenance or insurances, leading to faster and cheaper interactions for both entities [10]. Moreover, this transparency can also lead to quality-improved or longer-lasting products, as the enhanced knowledge of products and their usage enables, e.g., to schedule maintenance intervals on time or to adapt products to specific needs [95].

2.1.3 Customer-to-Customer Transparency

The discussed transparency benefits are not limited to business relationships, but also apply to interaction between customers. For example, direct reselling between customers is a market that significantly profits from information on the product's manufacturing and maintenance history, enabling buyers to infer more about the product's state before purchase. Access to this data could be realized via blockchain-based data markets, which also provide best practices for usage or settings considering productivity, low operating costs, or sustainability of products. As we focus on industrial use cases, we do not further discuss such customer-related benefits.

Concluding, establishing transparency with blockchain technology has several benefits. We note that, to realize these benefits, all involved entities (businesses and customers alike) must be accountable for the available data.

2.2 Decentralized Accountability (⊞ II)

Orthogonal to transparency (⊞ I), blockchain technology increases accountability (⊞ II) without requiring a central entity. By transparently recording information on an immutable distributed ledger, businesses obtain a reliable proof of business actions, relationships, and contracts. As discussed before, stakeholders are able to set up control mechanisms and identify misbehaving stakeholders. To this end, cryptographic signatures publicly link information on the blockchain to the providing party. Consequently, blockchain technology increases the trust between businesses.

To not jeopardize this trust, a key requirement is the resistance against collusion attacks. Especially in comparison to centralized platforms, where the deletion or even manipulation of information might only require a collusion of a few stakeholders, the decentralized approach of blockchains achieves a significantly higher degree of collusion resistance. In particular, already a simple majority of honest and well-behaving blockchain nodes [75] prevents data loss, manipulation, or deletion.

An open challenge, however, is to realize the insertion of correct information in the blockchain [96, 124]. Here, technical means are needed to ensure that the processed data is reliable and has not been tampered with before. Otherwise, all beneficial features of blockchain technology are rendered useless.

In the following, we specifically discuss the advantages of accountability for product data, business contracts, and behavior policies that promise to foster trust-based relationships between multiple businesses or towards their customers.

2.2.1 Data Accountability

Customers and businesses can profit from increased transparency and open, accessible information (⊞ I). However, the value of the shared information and the achieved transparency heavily depend on the originality, correctness, and completeness of the provided data. Consequently, only immutable and cryptographically proved information as, e.g., provided by blockchain technology, ensures the desired accountability. These properties thus strengthen the benefits of information transparency and corresponding enhanced business opportunities collaboration (⊞ III) [75, 97].

Furthermore, the decentralized handling of on-chain information obviates the need for a trusted third party. In combination with cryptographic proofs of origin, which link data to the providing party, businesses can be more confident about the correctness of data, enabling conflict resolution in case of disputes or misbehavior.

Moreover, holding businesses legally responsible for all submitted information or maintaining a publicly available reputation system [76] reduces financial risks while increasing the trust between involved businesses. A digital and reliable source of information further paves the way for more advanced approaches and their benefits, including sophisticated automation (⊞IV) and a fostering of digitalization (⊞V).

2.2.2 Legal Compliance

Another aspect that is closely related to accountability is legal compliance. Especially in competitive environments, making sure that all participants follow enacted laws is crucial to ensure a fair market. However, also from a governance (e.g., taxes), customer (e.g., warranty), and environmental perspective (e.g., sustainability), legal compliance is an important aspect. Here, blockchain technology offers different features to document and ease checking for legal compliance.

Most legislation requires businesses to document their actions and transactions. Blockchain technology offers a simple, digital way to securely conform with these requirements. This digital documentation can entail additional benefits, such as a complete and correct, but also simpler and more transparent, taxation [23]. Likewise, transparently recorded money flows could help uncover corruption [42] or identify illegal practices, such as sourcing material from sanctioned countries [23].

Another benefit for the legal domain is an increased digitalization (⊞V) which evolves from the pre-requirement to use digitized data to utilize blockchain technology. In the legal domain, this digitalization reduces barriers for the establishment of new business relationships. Specifically, maintaining a history on chain eases the negotiation of contracts as all relevant information is readily available. Thereby, lengthy checks for legal compliance are significantly shortened such that collaborations can be established faster and more easily. Thus, blockchains could simplify audits, reduce administrative costs, and speed up processes, e.g., by automating large parts of otherwise manual checks of paperwork [23]. In case of conflicts, contracts on chain represent a single undisputed view of the current situation. Consequently, the situation in legal proceedings is transparently documented and cannot be easily disputed, i.e., finding loopholes is more challenging due to publicness. These aspects not only hold for contracts between businesses, but also towards customers, e.g., blockchain-based insurances increase policy transparency, enable automation and ensure publicly verifiable legal compliance in case of claims (cf. Sect. 4.8).

2.2.3 Building Reputation

With accountability, companies can easily build up a well-documented reputation. This reputation can help to acquire more business partners or customers. Furthermore, new business relationships which yet lack trust can draw from publicly available information on past company behavior.

For e-commerce, blockchain technology could further realize a trustworthy reputation system. Similar ideas are known from the context of supply chains, and initial approaches realize such functionality using smart contracts [76, 122]. Likewise, the government can utilize blockchain technology to encourage the participation of both companies and citizens by publicly reporting the planning, execution, and reporting of processes in cities [37]. Some specific applications would be, e.g., to report and track waste or potholes. Overall, blockchain-based reputation can support all stakeholders in a domain and thus allows for well-founded decisions and actions.

2.3 Collaboration (⊞III)

In addition to transparency (⊞I) and accountability (⊞II), blockchain technology can further facilitate the collaboration between stakeholders by providing a shared and distributed medium for the required exchange. In this section, we highlight the benefits for already established collaborations and ad-hoc collaborations.

2.3.1 Benefits for Already Established Collaborations

The blockchain provides a unified interface for the provision of and access to trustworthy data shared between collaborators. Together with established trust levels in long-lasting collaborative relationships and a fine-granular access control realized with selective accessibility (details in Sect. 3.2), this unified data access enables novel applications. For instance, the unified and trustworthy interface facilitates the tracking and tracing of goods and products even over multiple hops of a supply chain [97]. Furthermore, a fine-grained exchange of detailed product quality information enables collaborators to adapt their machine settings when processing these products further, thereby avoiding low-quality results [97]. Finally, blockchain-based collaborations can improve Enterprise Resource Planning (ERP) across businesses [77].

2.3.2 Benefits for New or Ad-hoc Collaborations

Some industries face the challenge of relying on relatively short-lived or spontaneous collaborations. Especially small businesses and startups need to remain flexible regarding new collaborations as they often depend on frequently acquiring new collaborators [35, 45]. Furthermore, also more established industries with traditionally long-lived collaborations, such as manufacturing, are in the process of becoming more dynamic, e.g., through on-demand manufacturing in low quantities [31]. Both scenarios require stakeholders to spontaneously seek a collaboration partner and frequently engage in only short-lived collaborations based on their short-term needs.

Such an environment makes it hard for stakeholders to establish trust, and they thus require other means to assess a potential collaborator's assets.

Industry-wide blockchain-based platforms can provide the data source for an assessment of the trustworthiness of potential new collaborators [100]. By making use case-relevant data accessible for potential collaborators, businesses can reduce reservations of potential collaborators to establish a new, not yet trustworthy, business relationship. Thereby, the blockchain prevents those businesses from retrospectively altering past records, i.e., the transparency (⊞I) ensures a full view of past collaborations of the potential new partner. Furthermore, special blockchain designs such as *consortium* blockchains and mechanisms for fine-granular access control to blockchain data (which we detail in Sects. 3.1 and 3.2) can help to establish technical trust throughout the new or short-term business relationship.

2.4 Trustworthy Automation (⊞IV)

One key benefit of blockchain technology is the potential for higher degrees of automation. The concept of smart contracts fosters this association as they provide stakeholders with a framework for setting up mutually agreed rule sets that are automatically invoked based on new events being recorded on the blockchain. Especially using blockchain-extrinsic data sources, e.g., (I)IoT sensors [96], GPS data [41], or weather data [41], promises an increased potential for automating processes tied to the real world, between not fully trusting stakeholders. These potentials unfold over all industry-related interaction models, i.e., bilateral negotiation between individuals [119], customer-related processes such as processing insurance claims [10], business-to-business (B2B) interaction [49], and even fine-granular machine-to-machine (M2M) communication [53, 96].

In these scenarios, the blockchain provides a logically centralized place for the automated lookup of process-related data, providing an alternative to today's heterogeneous platforms for inter-business exchanges [74]. Hence, smart contracts could replace or augment traditional contracts and thereby simplify the processes between businesses due to a simplified drafting and interpretation of contracts [23]. Furthermore, the increased automation can ultimately increase both customer and employee satisfaction as well as the competitiveness, profits, and overall performance of businesses. E.g., increased automation can result in *easier payment processing* as well as *efficient M2M communication*, which we briefly discuss in the following.

2.4.1 Easing Payment Processing

Cryptocurrencies established an effective way for private users to realize low-cost and near-instantaneous international money transfers [113]. Likewise, collaborating businesses from different countries could agree on relying on cryptocurrency B2B payments to seize the same advantages [74]. In this case, B2B money transfers can further be automated as discussed earlier and thereby enable new and more dynamic forms of collaboration, such as manufacturing-as-a-service [95] and, in general, properly billed cross-business M2M communication [53].

Since blockchain transactions are typically visible for the participating stakeholders, smaller suppliers, such as gemstone miners with lower extraction capacities [112], can further profit from increased price transparency [112]. Finally, tiny stakeholders, such as household energy prosumers, can also benefit from reliable micropayments and transparency provided by blockchain technology [62, 82, 104].

2.4.2 Machine-to-Machine Communication

Referencing real-world data on the blockchain opens up new potentials for efficient M2M communication. By sensing data with trusted hardware, machines owned by different stakeholders can exchange information while mitigating the risks of data manipulation by a (partially) distrusted collaborator [96]. Furthermore, machines can use automated micropayments and potentially provide revenue in real time (cf. Sect. 2.4.1). Customer-oriented M2M micropayments are already used, e.g., to automate payments at gas stations [53]. Again, these payments build on technically enforced rules and can thus occur on the fly without further negotiation. In the future, other industries can seize these benefits, e.g., to fully realize the aforementioned manufacturing-as-a-service paradigm where smart production lines can directly bill any short-term customer based on a fine-grained tracking of used machine hours.

2.5 Blockchains Foster Digitalization (⊞ V)

The benefits provided by blockchain technology can only be achieved with a thorough digitalization of data and information in corresponding uses cases such that it can be provided to the blockchain. Many forms of digitalization would have been possible without blockchain technology, e.g., using simple digital signatures. However, we posit that the additional benefits of blockchain technology provide the required strong incentives to finally make digitalization happen in many domains. E.g., as briefly discussed in Sect. 2.2.2, the use of blockchain-based smart contracts fosters digitalization in the legal domain. In contrast to traditional paperwork, digitalized data on blockchains is virtually always accessible, properly indexed, and supports fast automatic (keyword) searches. In the following, we showcase the potential of blockchain-backed data management to *supersede intermediates*, discuss how *digital certifications* can provide fast and trustworthy attestations about products, businesses, and even employees, and show to which extent blockchains can facilitate the negotiation and enforcement of *contracts* while reducing the required paperwork.

2.5.1 Disintermediation through Blockchain-backed Data Management

Digital paperwork allows for timely and automated access to relevant documents due to instant availability and fast searches based on digital indexes. As we discussed for blockchain-based collaboration (⊞III), maintaining such a document index on the blockchain also allows for a fast and automated exchange of documents between businesses. Furthermore, the blockchain's immutability ensures the authenticity of requested documents. Using a blockchain with selective accessibility (cf. Sect. 3.2) additionally enables businesses to use corresponding benefits in a non-public setting which further facilitates document-dependent business processes, such as reporting to collaborators or the exchange between businesses' legal departments, by reducing human interaction to managing access control. This vast reduction of required interaction along with a smaller chance for errors enables a form of *disintermediation*, i.e., avoiding tasking trusted third parties with organizing required document exchanges [88]. Corresponding benefits have been seized in multiple proposals already, e.g., in the contexts of shipping containers [52], diamonds [36], or insurances [10].

2.5.2 Expressiveness of Digital Certification

Digital certification can help businesses to establish a reputation, e.g., by getting certificates for products, product properties, or production processes [65], while reducing the organizational overhead and paperwork associated with the certification processes [102]. Furthermore, employees can generate electronic portfolios based on digital (micro) accreditation, e.g., in the form of Open Badges [3], which attest their skills and experiences. Blockchain-based platforms have naturally been identified as a candidate for hosting such digital certifications [47]. Linking such a certificate immutably to a blockchain underpins the certificates' trustworthiness as multiple independent parties can acknowledge its authenticity [46]. In cases of a fully digitized certification process, e.g., in the context of e-learning, a complete automation of the process, including an immutably stored certificate on the blockchain, is conceivable. Furthermore, if businesses also link all data required to become certified to the blockchain in a selectively accessible way, corresponding audit processes can be digitized as well and thereby reduce costs and resources blocked by ongoing audits. Finally, blockchain-based certifications can be extended further without risks of fraud to, e.g., certifying the sustainable processing goods along a whole supply chain.

Thereby, digital certification can be seized in different industrial applications. On the one hand, in addition to the origin of goods, e.g., gemstones and fish, environmentally responsible businesses can receive an attestation of their sustainable sourcing of goods and other materials [33]. On the other hand, unified and immutable certification via industry-widely used blockchain-based platforms helps to disambiguate conflicting claims. For instance, recording transactions of assets, such as land ownership, on a blockchain makes it easier to decide conflicts, e.g., stemming from conflicting ownership records, and prevent further fraud [15, 74].

2.5.3 Blockchain-backed Contracts

Beyond the automation of inter-business processes through smart contracts (⊞IV), blockchain technology can also improve paper-based contracts. By disclosing their expertise on a blockchain, e.g., in the form of an audited digital certification, businesses can easily identify potential collaborators (⊞III) using the blockchain as a centralized repository of business capabilities and offered services. This information can serve as a foundation for new contracts, as responsibilities can be expressed in reference to the (claimed or attested) capabilities.

Furthermore, a blockchain can also hold terms and conditions specified by one business partner and immutably record the collaborators' dedication to abide to these terms. This approach is especially beneficial when handing over intellectual properties. For instance, creators of educational material may sell their content over a blockchain-based market that records license terms [80]. Comparable approaches can be transferred to other, especially data-centric, industrial applications.

3 Challenges and Design Spaces for Industrial Blockchains

Initial use cases for blockchains focused on public services such as digital currencies [85], general-purpose frameworks for smart contracts [123], or digital notary services for existence proofs of data [14]. Contrary to these public services, realizing the blockchain benefits for industrial applications and the Industry 4.0 discussed in Sect. 2 requires addressing complex challenges regarding storage and accessibility of data. More specifically, industrial use cases often have tighter demands on (i) who controls the blockchain's infrastructure, (ii) access control for data stored on the blockchain, (iii) scalability considering growing infrastructures, numbers of users, and data volumes, and (iv) the efficiency of the blockchain, i.e., preventing the blockchain from becoming a performance bottleneck. In the following, we discuss design options that address these demands on blockchain-based systems and thus realize the envisioned benefits for Industry 4.0.

3.1 Control over Blockchain Infrastructure

Public blockchains—as used by initial deployments—provide relatively small control over who can insert which data and require expensive consensus mechanisms to protect against malicious actors. These restrictions are, however, only necessary if not all contributors are known beforehand [124], which is rarely the case in industrial scenarios. Still, industrial applications can seize the benefits of established public blockchains (i) as a decentralized trust anchor, (ii) for access to a widespread digital currency, and (iii) for a resource-less integration. In contrast to public and trustless systems, industrial stakeholders pushed *private blockchains*, which are controlled by a single entity. While the applications of such blockchains are limited since all users must trust a single stakeholder, they are sufficient, e.g., if a parent company sets up a blockchain for its subsidiaries [56]. In exchange, they can rely on a much more efficient consensus mechanism for increased data throughput and reduced maintenance costs [83]. *Consortium blockchains* present a hybrid approach that distribute control among a group of known stakeholders to obviate the trust in a single entity while still supporting efficient consensus protocols. As consortium blockchains only require partial trust among entities, they are attractive, e.g., for supply chain management.

3.2 Access to Blockchain Data

Beyond the control over the blockchain infrastructure, industrial applications also often require tight access control for data stored on the blockchain. We distinguish three basic access levels: *public*, *stakeholder*, and *selective* accessibility. Public accessibility is, e.g., suitable to achieve high transparency regarding the ethical, sustainable, and regulation-abiding handling of goods [24, 50, 66, 87]. However, publicly disclosing production or other business-related data risks that data is exploited to infer sensitive information about customers, business partners, or production processes [124]. Thus, public data has to be carefully selected, and more restrictive data access models need to be applied for sensitive data. Stakeholder accessibility presents the contrary extreme where only the blockchain-maintaining nodes can access blockchain data. This model is suitable for internal accounting and tracking of events without (automated) access for outsiders. It furthermore often matches the demands of use cases with private or consortium blockchains, which typically serve internal processes. Finally, selective access to blockchain data can be achieved via fine-granular access control systems [97] that enable operators of private or consortium blockchains to selectively disclose blockchain data to outsiders, e.g., known customers or subcontractors, while keeping internal data secret. However, this flexible model burdens blockchain nodes with key management overheads.

3.3 Scalable Blockchain for Massive Amounts of Industrial Data

Industrial use cases likely challenge the scalability of blockchains with respect to the amount of stored or referenced data on the blockchain. For instance, industrial use cases that monitor production processes can produce massive amounts of data through large numbers of heterogeneous sensors with potentially high sampling frequencies. This data volume remains challenging concerning the throughputs of today's blockchain systems. Private or consortium blockchains can help to meet scalability demands as they limit the number of participants and achieve larger throughputs (cf. Sect. 3.1). Still, data-intensive use cases such as monitored production need further options. Using *data aggregation* to only extract and store the relevant information from generated data on the blockchain can, e.g., reduce throughput requirements [96, 126]. Another option is to only store small identifiers of large data and cryptographically link them to scalable a *off-chain storage*, e.g., distributed hash tables [110, 130], the Interplanetary File System (IFPS) [89], or cloud storage [127]. Furthermore, obsolete data, e.g., information about drugs that exceeded their date of expiry [59], can be *pruned* from the blockchain to free valuable storage [79, 81].

3.4 Efficiency of Blockchain Operation

Finally, some industrial use cases depend on low latencies of blockchain writing processes. For instance, future power grids use a latency-dependent coordination (cf. Sect. 4.4), whereas traditional blockchains incur delays of several minutes. To overcome these delays, industrial use cases can realize low-latency data insertion via mainly two options: *efficient consensus mechanisms* or *off-chain computations*. Private or consortium blockchains can achieve a quick use of blockchain data through efficient consensus mechanisms, which can be further enhanced if participants trust the maintainers and do not wait until immutability is achieved through technical means. Furthermore, critical operations can be shifted off-chain, e.g., financial transactions during energy trading (cf. Sect. 4.4) can be processed through micropayments channels [21, 29], where the sender and receiver of digital currency repeatedly exchange valid transactions without sending them to the blockchain. Similarly, complex smart contracts can be executed off-chain if latencies or costs become prohibitive.

4 Use of Blockchain Technology in Industrial Domains

In this section, we provide an overview of blockchain integration by different and heterogeneous industries and the achieved benefits. Thereby, we consider the general benefits of the technology (cf. Sect. 2) and map them to real-world benefits for industries from different domains. To identify both common and industry-specific obstacles for seizing the benefits of blockchain technology, we cover industries from the primary, secondary, and tertiary sectors in our case studies.

4.1 Engineering and Manufacturing

One prominent industry that benefits from blockchain technology is the engineering and manufacturing industry. The reliability and quality of products are especially crucial when they constitute integral parts of larger systems with corresponding catastrophic consequences in case of failures. Sharing information along the supply chain can, e.g., increase product quality and reliability, reduce redundant work, establish more trustworthy product data, strengthen auditing processes, detect potential issues in an early production stage, and ease product recalls [11, 70, 75, 97, 117].

Notably, sharing this information with potentially unknown and untrusted businesses entails the risk of exposing critical business secrets, e.g., production volumes and quality [124] or collaborations [11, 97], and collaborators may intentionally share imprecise or wrong information [95]. The use of consortium blockchains, however, can mitigate these risks by realizing selective accessibility with permission control and accountability. Thus, blockchain technology can play a crucial role in enabling the sharing of authentic data along the supply chain [40]. More specifically, it realizes a unified view among participants via data consistency, increasing trust in the shared data and preventing counterfeit products from entering supply chains or end customer markets [52]. Thereby, use cases still can use fine-grained access control and benefit from transparency, consistency, and immutability. Even more, the integration of data sharing into manufacturing processes facilitates auditors' and certifiers' work, enabling continuous certification processes instead of only periodic audits [117]. These processes can even completely forgo a trusted third party and instead rely on automatic and verifiable processes based on a blockchain [40].

Besides collaborating with respect to individual products, collaboration extends to sharing of domain knowledge [98], manufacturing equipment [117], and common long-term goals [117]. Digital machine data marketplaces aim to collaboratively optimize production processes by sharing data on unforeseen machine failures or production issues with business partners or even competitors [117]. Without blockchain, the reliability and availability of such information are limited as a verification of origin, integrity, and validity of the data is missing [117]. A blockchain can improve the verifiability of these aspects by transparently and immutably recording data acquisition metadata and providing the foundation for a decentralized data marketplace where information itself becomes a monetary good [99, 117]. Ultimately, sharing domain knowledge on such a decentralized data marketplace paves the way for establishing digital factories [99] and reduces costs for process optimization in the companies themselves [98, 117]. Thinking even further, sharing equipment and machines in a pay-per-use model using a decentralized blockchain-based application for payments and machine management promises both a better utilization and a highly-flexible use of machine pool capacities [117]. Finally, blockchain technology can facilitate addressing collaborative goals such as optimizing a consortium's environmental footprint [117]. Transparently and collaboratively managing aspects such as recycling or carbon emissions with the help of on-chain contracts in combination with financial benefits for "green" companies provides an additional motivation to reduce their environmental impact as they can prove their achievements to end-customers.

4.2 Lumber Industry

Besides the manufacturing industry, also industries concerned with raw materials production can benefit from blockchain technology. We focus on the lumber industry, where illegal timber harvesting causes estimated annual damages between USD 51 billion and USD 152 billion [125]. Preventing illegal logging protects biodiversity and forests, reduces carbon emissions, and enables sustainable forest management [125]. Also, customers increasingly care about *trustworthy* sustainability information [87]. However, current protection mechanisms against illegal logging, e.g., the *EU Timber Regulation*, lack effective auditing, and detected anomalies are not properly prosecuted: Paper-based certification approaches are opaque, inefficient, and easily tampered with [125]. Blockchain technology has been envisioned as a key building block to tackle corresponding challenges [33, 87].

While both customers and the overall industry share the desire for sustainable products [8], these demands typically affect only the customer-sided end of a supply chain and not the raw materials producers [87]. Consequently, even honest end-producers have to trust the paper trail of their suppliers and thus cannot abundantly guarantee the usage of sustainable and conflict-free raw materials. Blockchain technology promises more efficient, trustworthy, and holistic tracking of a product's origin and sustainability by making the data records immutable and publicly accessible. In contrast to paper-based certification, the division, merging, and replication of certificates of origin can be easily prevented through blockchains properties. Realizing a trustworthy certification process would also enable the import of timber from regions that are currently not considered for trade by many companies due to an elevated risk of breaching the law in western countries [33].

While the transparency provided by a blockchain eases fraud detection and thus makes it hard for individual stakeholders to systematically cheat within their supply chain, ensuring authentic data requires additional efforts. Here, proteomics can provide physical evidence of the correctness of blockchain data [33]. Furthermore, IoT sensors, GPS location trackers, RFID chips, bar codes, and point-of-sales data provide additional information to detect inconsistencies of blockchain data [87]. However, finding an optimal inconsistency detection method is still an open research problem. Furthermore, the underlying blockchain has to support multiple hundred parties, producing over 100,000 transactions per minute [33]. Nevertheless, even today, the transparency and data consistency offered by blockchain technology could make the lumber industry fairer, more sustainable, and more competitive, which makes its use attractive for end-consumers, producers, and even regulators.

4.3 Petroleum Industry

The petroleum industry primarily deals with the detection, extraction, refining, and transport of crude oil. This resource is an important component of many products, including fuel, plastic, and pharmaceuticals, and will thus remain important for the next decades. This industry is controlled by a few big and established players, mainly because crude oil extraction is profitable only at large scales and limited to a few regions of the world. Despite the industry's known resistance to change, established big players and new startups alike explore the integration of blockchain technology into their processes, showing its potential to benefit the industry [74].

Blockchain technology can even help before any crude oil extraction takes place. Companies spend significant amounts of money for managing land claims to extract oil. Here, a significant amount of conflicting claims frequently leads to disputes [74], and fraud in land transactions is rather common, especially in less developed regions [15]. In these regions, land registrations are often still managed on paper, and records are kept in a single location [15]. This situation leads to inefficient processes, inconsistent information, the potential of data loss, and manipulation due to the lack of redundancy and backups. Managing land claims via a blockchain-backed system would consequentially tackle these problems and provide additional benefits over a decentralized database: transparency and tamperproofness ensure a globally consistent state of land claims, digitized contracts enable automation to reduce costs and processing time, and public trades prevent corruption [15]. Yet, corresponding changes are hindered by a lack of expertise and political resistance to changes [15].

After extraction, crude oil usually crosses several borders and is traded multiple times on the path to its destination, involving numerous middlemen [106]. Blockchain technology can increase automation for these processes and establish transparency, which speeds up tax audits, reduces administrative costs, and tackles delays due to paperwork validation, e.g., by intermediate traders [23]. Blockchain-based processes could, e.g., tokenize individual barrels of oil or replace traditional with smart contracts that, e.g., automatically execute buy orders upon governmental approval [23, 74]. Overall, these improved processes would lead to fewer disputes (a significant problem in the industry [23]) and misunderstandings by eliminating ambiguities and reducing the amount of work to draft and interpret contracts while simultaneously reducing the necessary efforts to prepare for eventual conflicts [23, 74].

Another aspect of the petroleum industry that can be significantly improved upon by blockchain technology is payment processing, either by handling payments on chain, or by sharing provably consistent information with all involved parties. Here, the petroleum industry can especially benefit as multiple parties are involved in a single trade, trades involve large sums of money, and trades happen while the ware is in transit [106]. First, post-transaction management, which currently occupies banks for several hours per trade due to employing special scrutiny, can be sped up by sharing information on a blockchain [106]. Second, the trusted environment offered by a blockchain enables the entities in the petroleum industry to cut out intermediaries [74]. Finally, the transparency of blockchains eases fair and transparent taxation even when the traded oil is traveling across the world [23]. This fair taxation benefits governments and businesses alike, as it ensures that all trades are taxed correctly [23]. Furthermore, blockchain technology is beneficial in legal aspects. In particular, the transparency of blockchains enables easier and faster verification of abidance to ever-changing global sanctions and environmental laws [23], as well as helps in preventing and uncovering corruption [42, 74].

4.4 Energy Industry

The energy industry, i.e., businesses that manage continental, national, or regional power grids, and feed energy into them, experiences extensive changes regarding the power grid's structure and the applied business models. Traditionally, power is produced in the "core", e.g., by large power plants, and traverses long distances via the transmission grid to local distribution grids, e.g., serving a smaller region consisting of several small towns. The increase in renewable energy plants, e.g., solar power plants and wind turbines, results in a distributed power production and more complex grid management, especially as local energy production might exceed or fall short of local demands, depending, e.g., on the weather. Further, individual households might be producers and consumers (prosumers) at the same time, e.g., houses equipped with photovoltaic arrays can flexibly import and export energy. Energy storage systems in private households further enable a fine-granular control *when* to buy or sell energy, further increasing the energy market's complexity [5]. *Local Energy Markets (LEMs)* even enable energy trading between prosumers [82] and local consumers to achieve a better cost-efficiency as if buying energy from the grid providers. Trading between multiple LEMs can further contribute to this cost-efficiency, but requires even more advanced synchronization and coordination [82].

Blockchain technology offers multiple benefits for such peer-to-peer environments by realizing a decentralized, yet accountable trading [108]. With the help of blockchain, LEMs can independently trade excessive energy in a decentralized manner [82]. Meanwhile, blockchain technology can also help coordinate energy consumption to stabilize the power grid [5]. Depending on the specific requirements, both consortium blockchains and public ledgers are applicable. Existing approaches already consider several aspects of this trade, such as digital currencies [82], on-chain contracts [84], privacy enhancements [38], and transparency of local trading [38], whereby price transparency enables fairer competition and pricing policies [51].

Another application of blockchain technology in energy-related industries deals with the internationally regulated trading of carbon emission licenses [4]. In contrast to LEMs, blockchain-based carbon emission applications aim to enable on-chain business-to-business contracts and trading. Companies that cannot meet their carbon emission targets can buy *emission credits* from those companies that have excess credit [4]. Similar to LEMs, carbon emission trades benefit from decentralization [68] and wide-ranged (pricing) transparency to increase competitiveness and prevent extortion and monopolies. Besides decentralization, existing approaches such as the Bitcoin-based carbon emissions trading platform D-CETI [4] consider further aspects, covering privacy, dedicated currencies, and efficiency measures.

4.5 Food Supply

A field that is even more critical to humanity than the energy industry is that of food production and supply, which represents a further beneficiary of blockchain technology. There is an increasing demand of consumers and business partners to reliably determine the origin, ingredients, and quality of food products as well as to obtain knowledge about animal and worker treatment as well as the fulfillment of food label requirements [64]. As food supply chains comprise various actors with different incentives, ranging from farmers over producers to retailers, blockchain technology is seen as a major innovation driver for the industry's future [64, 69, 72, 111].

As a first benefit, information on production and transportation parameters can be reliably recorded on blockchains. Information, such as temperature readings in warehouses and trucks, aid the detection of interruptions in cold chains [96, 124]. While an accountable monitoring of products can increase customer satisfaction by transparently communicating this data, it can also reduce costs for producers, e.g., by reducing food waste [72, 128]. Two general concepts to share such production and transportation information are applicable. First, the history of each product can be individually monitored with the help of QR codes, RFID chips [115], and sensors [124]. Alternatively, accountable information sharing for all or a random sample of products and involved businesses enables companies to provide reputation-based proofs of their reliability to partners and customers. In particular, a customer learns how involved businesses fulfill certain requirements based on past and recent data elicitations. While customers benefit from fine-grained information on individual products, such granularity is more challenging and costly to achieve.

Secondly, tracking individual products and their ingredients along the supply chain from the initial producer, e.g., the farmer, to the final customer, enables advanced quality assurance to, e.g., identify contaminated food [64, 111]. While blockchain technology would not add benefits in an ideal world where all involved businesses collaborate to identify affected products, contaminations lead to financial and reputational damage for the responsible businesses, such that they have an incentive to obfuscate incidents and hinder investigations. Hence, the accountability and transparency of blockchain technology are valuable to acquire reliable information regarding the production of individual products. Thus, the digital trace of products can aid in the reliable and fast identification of other contaminated product batches.

Thirdly, blockchains can aid to achieve accountability and transparency for food labels, e.g., organic and *Designation of Origin Collected and Guaranteed* (DOCG) food [6], kosher [32], halal [12], and vegan [32] food. Foremost, blockchain data prevents an inappropriate relabeling of food, e.g., labeling horse meat as beef [105]. Similarly, food certifications and seals such as fair trade-related labels [103] or the MSC fishing label [91] can benefit from blockchain-based transparency as customers get a more detailed insight into the production process. However, maintaining accountability along multiple hops of the supply chain remains challenging.

4.6 Logistics

Beyond the transportation of food, the whole logistics industry, which delivers wares to business partners, is a natural candidate for blockchain applications. The industry currently spends roughly USD 360 billion annually on the administration and documentation for moving goods across borders [106]. Blockchain technology offers one building block to reduce these costs by enabling the distributed tracking of shipping documents, e.g., customs forms and bills [106]. This distributed tracking reduces delays and costs compared to manual information sharing among all entities while preventing inconsistencies. Such a blockchain-backed process even enables the automatic initiation of follow-up steps, e.g., bill payments [30]. Additionally, such a process prevents the alteration, theft, or forgery of documents [52], decreasing legal and administrative costs for settling disputes.

Beyond easing paperwork, blockchain technology can also improve the planning of shipments. Blockchains offer a trusted platform for data sharing, such that all stakeholders view the same data. Therefore, businesses can collaborate without arbitrators, enabling a more efficient, automated, and error-free managing of transportations [30]. These benefits are not only available to established partners, but also to short-term cooperations, since positive historical data enables a company to build up a good reputation for its service. Thus, blockchain technology enables the efficient use of crowdshipping, where one shipping company can use up the remaining capacities from a (previously unknown) competitor [65]. This benefit is not only profitable for both companies, but is also efficient for the environment due to reduced greenhouse gas emissions. Specifically for new and short-term relationships between companies, other benefits, e.g., insight into partner's reputation, faster and cheaper cross-border payments, certification of green vehicles, or management without a trusted intermediary, make the use of blockchain technology attractive [65].

Similar to other industries, having trustworthy information available on the responsible and sustainable handling of products during its transportation is also attractive to end-customers of goods [65]. Sustainability information, in the form of the carbon footprint of a product's transportation, benefits especially, since the current disclosure of this information is, due to different reporting methodologies by various subcontractors, not done homogeneously across the logistics industry [55]. Finally, if issues arise during a product's transportation, readily available, detailed, and transparent tracking information allows for fast issue identification and potential fault recovery as well as the identification of the responsible entity [116]. Unfortunately, such issues are not handled satisfactorily in many cases today, since necessary information is hard to retrieve, missing, or simply not available [116].

4.7 Waste Management

Besides improving sustainability in many previously discussed use cases, blockchain technology can also have a major impact on waste management, one of the most important industries in realizing a more sustainable and less wasteful lifestyle. Waste management encompasses three major aspects: extending a product's lifetime, recycling disposed products, and responsibly handling unavoidable waste. All these three aspects are handled suboptimally today, mainly because of various involved actors with (partially) opposing incentives and goals. Blockchain technology can improve the current situation by generating trust among these distrustful parties, providing transparency, ensuring accountability, and enabling short-term collaboration.

To extend a product's lifetime, a product must be maintained properly and easily resellable when it is no longer needed by the original owner. The former can be improved through blockchain technology by enabling active maintenance management, i.e., a product, e.g., some machinery, is equipped with sensors that collect data to proactively schedule maintenances when, e.g., production cycles or sensor reading pass a threshold [73]. Here, blockchains could manage the relation between product owner and maintainer to ensure adequate, but not excessive maintenance, and to provide the maintainer with a tamper-proof history of a product's usage [73]. This history can also be used to make educated decisions on when to update or replace existing hardware [73]. Having access to a reliable history of a product is also important when it comes to reselling, e.g., a car checkbook as trusted history significantly influences a car's resale value and hints at the state of the vehicle. Such benefits can extend to other products, benefiting resellers and buyers alike. If reselling is also managed transparently on the blockchain, this information could provide buyers and sellers with price estimates for products based on statistics of former trades of products in similar conditions [73]. Blockchain technology can also pave the way to ensure second-hand customers that a product was sustainably and environmentally-friendly produced [65], which can further increase resale values [48, 92].

Blockchain technology can also improve product recycling at the end of a product's life. Here, it facilitates finding short-term business partners that may have a use for disassembled products, e.g., rubble from a demolished building can be used by a construction company, saving costs for both parties [65]. However, as recycling is not always lucrative, laws and regulations are often ignored. Here, blockchain technology can improve coordination between various actors and establish transparency to properly enforce laws [50]. Additionally, blockchains can realize a fine-grained incentive system that encourages recycling through micropayments [66]. Finally, blockchain technology can be used to certify new products that are built from recycled goods. Providing customers with this information in a trustworthy way also benefits the product sales, since the likelihood of people buying green products increases with the trustworthiness of the certification [48, 92].

Lastly, unavoidable waste is often not appropriately disposed of, and thus, harmful to the environment. The US alone spends multiple million dollars annually on the cleanup of poorly managed landfills [65]. While transparency on *claimed* behavior is not directly revealing the entities responsible for illegal waste disposal, it allows potential collaborators or customers to verify which parties are honest and reputable, thus facilitating prosecutions by narrowing the number of potential malicious actors. Additionally, blockchains can arrange the waste disposal process when no entity is trusted or willing to manage the process, e.g., for cross-border waste disposal [90]. Such a change could enable more efficient waste flows and faster administration with less overhead. Finally, blockchain technology offers the foundation for systems where citizens can interact and contribute to public bodies [37]. Such systems can be used to publicly report and track, e.g., waste or potholes in cities and their remediation [114].

4.8 Insurance Industry

A second service industry that sees major research into the use of blockchain technology is the insurance industry [10, 13, 16, 26, 41]. Insurances rely on contracts between the insurer and the customer to define the conditions that must be met to legally force payments to the customer. However, the business model of insurances suffers from contradicting interests of insurers and customers, i.e., in the case of damages or losses, customers demand fast and unbureaucratic payments based on comprehensive rules. Contrarily, insurers aim to minimize their expenses to achieve higher profits and better competitiveness. As a consequence, the corresponding insurance contracts tend to exhibit excessive complexity leading to unsatisfied customers. Furthermore, the insurer usually conducts advanced investigations in case of significant claims to counter fraud by malicious customers that try to trick the insurer by providing unjustified claims [7]. To improve the handling of claims in this complex field, the insurance industry investigates blockchain technology as a way to improve insurance policies by simplifying associated processes, speeding up claim processing, and providing transparency for decisions. Thus, blockchain technology can achieve higher customer satisfaction and, at the same time, increase the business performance of insurers, e.g., by attracting new customers through their reputation or a reduction of work-intensive (and thus costly) investigations.

A common use of blockchain technology in the context of insurance is to model the insurance policy as a smart contract and to automate behavior, e.g., by linking sensors [10, 26, 41]. Representing the insurance policy as a smart contract increases the transparency towards the customer as the policy becomes publicly verifiable [41], and—considering the complexity of traditional representations [10]—potentially improves the comprehensibility. Further, the conditions for successful claims are pre-defined, which increases the trust of the customers towards the insurer [10]. As a result, claim processing can be automated, simplified, and sped up.

Beyond specifying policies as on-chain smart contracts, the linking of external information promises additional benefits for insurances. Sensor data, e.g., for home or car insurances [10, 26], can speed up the processing of insurance claims and optimally even issue automated payments. Similarly, fine-granular pricing models, e.g., pay-per-use policies where the costs of a car insurance depend on the driving behavior of the customer [41], can be realized when linking sensors to an on-chain contract. However, sensors recordings can easily interfere with privacy demands or regulations, such that respective approaches require sophisticated privacy preservation measures. Applications that do not require private customer information, e.g., anonymized travel insurances with automated payback in case of canceled flights or trains [16], or automated payments for crop damage reported by external weather data [41], exhibit lower hurdles for the deployment of blockchain-backed solutions.

Finally, while traditional insurance relationships require the insurer to be a superior and centralized entity, blockchain technology enables peer-to-peer insurances without the need for a centralized and trusted third party [41]. To this end, the combination of the distributed ledger and one or multiple smart contracts takes the role of the previously centralized insurer and manages capital, policies, and the handling of claims. While initial platforms have been proposed [27, 101], ensuring appropriate financial reserves as well as fraud-resistant, reliable, and legally binding claim handling remains an active challenge for peer-to-peer insurances.

4.9 Gemstone Mining

The increasing desire for sustainable products [48, 92] also extends to luxury goods [28, 86]. Especially responsibly sourced gemstones are in high demand as the industry has a bad record for being exploitative [121]. Consequently, gemstone certificates, such as *GIA Diamond Origin Reports* and *AGTA Certificates*, are an important part of high-end gem and jewelry markets [24]. Various certification processes offer different levels of protection against fraud by relying on legislature, deploying third-party observers, or analyzing the chemical and physical properties of each stone in a lab. However, these certifications are still susceptible to fraud and entail significant costs [112]. Blockchain-backed certification efforts can be more secure, informative, and reliable as they provide immutable records of origin, allow for continuous tracking of the gemstones' ownership, and provide this information transparently to the public, thus giving businesses a competitive edge [112].

Still, the correctness of uploaded certification information has to be ensured, for which several preemptive and reactive measures have been proposed. Preemptive measures comprise, e.g., the soaking of gemstones in mine-specific nanoparticles that fill small fissures and present a unique property that can be linked to the blockchain [24]. However, this approach requires advanced technology and logistics. It is further inapplicable for pure elements, e.g., diamonds [24]. Other preemptive approaches range from data entry validation by third parties, over the engraving of small QR codes, to the insertion of RFID chips into pearls [24, 112]. Reactive measures comprise physical or chemical analysis to verify the correctness of blockchain data and raise alarms in case of anomalies. Additionally, a global view on supply movement enables the detection of systematic cheating with expensive lab analysis of random samples. Compared to a paper-based certification, blockchain-backed certificates hence offer new mitigation mechanisms against fraud, and can additionally store tracking and tracing information over a gemstone's lifetime. Thus, these certificates can, e.g., attest that a gemstone was not involved in illicit practices [112].

Blockchain technology can further benefit businesses in the gemstone industry by, e.g., reducing the need for intermediaries and trusted third parties to verify, audit, and certify the supply chain [112]. Furthermore, blockchains offer easier accounting and better interoperability between businesses due to a uniform interface and transparent information [77]. These benefits also apply to (small-scale) miners, benefiting from price transparency and thus fairer pay if blockchain-backed payments systems are deployed [112]. Finally, supply chain transparency makes it easier to ensure compliance with laws and regulations by governmental agencies [112]. The latter benefit is especially relevant since current schemes to ensure conflict-free gemstone supplies, e.g., the *Kimberley Process*, are increasingly put into question for lack of effectiveness and transparency [44, 63]. Consequently, the council members behind the *Kimberley Process Certification Scheme* actively seek to strengthen their certification process through blockchain technology [67].

5 Blockchain Technology for Industry 4.0 – The Big Picture

Previously, we analyzed the benefits of blockchain technology for industrial applications, discussed challenges that emerge when striving to apply it in industrial scenarios, and surveyed mature ideas and deployments for blockchain-supported industrial use cases. In the following, we discuss the gathered insights from a broader perspective. Specifically, we classify the relevance of blockchain benefits for different industries and identify corresponding future research challenges.

5.1 Assessing Blockchain Benefits for Industry 4.0

As presented before, the transparency (⊞I) and accountability (⊞II) available to blockchain-enabled use cases benefit nearly all kinds of industries. The use of blockchains promises to, e.g., foster collaboration, optimize production processes, advance automation and payment processes, ease trustworthy offloading of tasks, enable product life cycle tracking, improve monitoring of legal compliance, and encourage digitalization. All of this contributes to higher profits and an improved product or service quality under the paradigm of a yet unachieved level of transparency between collaborators, towards customers, or even for the general public. Other businesses increasingly value secondary goals, such as increased customer satisfaction or an improved environmental footprint, due to the potential gain of reputation. Blockchain technology is thus relevant for many industries.

To classify the importance of blockchain-based improvements, we provide a qualitative overview of the relevance of envisioned benefits for the discussed industries in Table 5.1. Where literature lacks corresponding information, we derive the relevance from industries with similar properties to provide a comprehensive picture. We posit that our overview can similarly hint at the relevance of benefits in industries not covered in this chapter, e.g., the drug production industry [1, 17].

Transparency. Transparency is relevant for all covered industries. Especially transparency between companies or between a business and their customers exhibits a broad relevance, while customer-to-customer transparency is only relevant for a subset of industries. Here, the gemstone industry has been identified as a leading beneficiary, since these high-value goods suffer from criminal intrigues, i.e., the trading of blood diamonds, while both, customers and involved businesses show a salient awareness of this issue. Furthermore, industries that qualify for peer-to-peer applications or second-hand markets, i.e., the energy market, insurances, and waste management businesses, can also profit from customer-to-customer transparency.

	Manufacturing	Lumber Industry	Petroleum Industry	Energy Industry	Food Supply	Logistics	Waste Management	Insurance	Gemstone Industry
Transparency (⊞I)									
Business-to-Business	●	●	◑	◔	◕	●	◕	◔	●
Business-to-Customer	◑	●	◔	◕	●	●	◕	●	●
Customer-to-Customer	○	○	○	◕	○	○	◑	◑	●
Accountability (⊞II)									
Data Accountability	●	◕	◔	◑	◕	◕	◕	●	◕
Legal Compliance	◔	◕	◕	○	●	◕	◑	◑	◕
Building Reputation	◑	◔	◔	◑	◑	◕	◑	◕	●
Collaboration (⊞III)									
Already Established	◕	◑	◕	◑	◑	◕	◑	◔	◔
New and Ad-hoc Collaborations	●	◑	○	◕	◑	●	◑	◕	◑
Automation (⊞IV)									
Easing Payment Processing	◕	◑	●	●	○	◔	◔	◕	◑
Machine-to-machine Communication	●	◑	◔	◕	◑	◑	○	●	○
Fostering Digitalization (⊞V)									
Disintermediation	◔	○	◑	◕	○	◔	○	◑	◕
Digital Certification	◕	◕	◔	◔	●	◕	◕	○	●
Blockchain-backed Contracts	◕	◔	◕	◕	◔	◕	◔	●	◔

relevance: ○ none ◔ limited ◑ partial ◕ significant ● exceptional

Table 1 Relevance of blockchain-based benefits for different industries. We provide a relative and qualitative relevance classification, ranging from none-existent ○ to exceptional ●. The relative importance differs for each industry, but each benefit is relevant for almost all industries.

Accountability. As argued before, transparency requires accountability to unfold its full potential, such that industries that demand transparency tend to similarly benefit from data accountability. Beyond that, the blockchain's potential to enable or improve legal compliance especially benefits industries with strong legislative regulations, e.g., the oil, food, and logistics industries, or where malicious or even criminal actors are historically expected, e.g., the lumber and gemstone industries. Furthermore, the possibility to build up reputation shows a significant relevance for those industries where (i) customers directly take part in the industrial applications (e.g., Local Energy Markets (LEMs)), (ii) customers and related businesses are especially aware of issues or care for high quality and specific product properties (food, logistics, gemstones), or (iii) the customer would be directly affected by inappropriate actions of the involved businesses (e.g., with insurances).

Collaboration. Businesses benefit from building reputation via blockchain technology when they are able to attract new end customers or establish new business relationships and collaborations. The ability to foster collaborations is especially relevant for industries that observe high volatility in their business relationships, e.g., manufacturing, logistics, and insurances. Contrarily, the petroleum industry exhibits rather rigid business relationships with limited capabilities for establishing new relationships, but still profits from transparency and reputation as they aid to maintain the existing relationships in the face of many legislative regulations.

Automation. Automation-related use cases profit from on-chain contracts that offer transparent data handling mechanisms as well as digital cryptocurrencies. Eased payment processes benefit the energy industry with its peer-to-peer applications, the insurance industry, where automated payments promise to reduce administrative expenses and increase customer satisfaction, and the petroleum and manufacturing industries, which depend on international trades or machine-based digital payments.

Fostering Digitalization. Finally, blockchain technology removes the necessity for a trusted third party, which is of special relevance for digitalized payment processes in international settings (petroleum and energy), to avoid pricing monopolies or account for low-trust and potentially criminal stakeholders (gemstones). For the latter, digital certifications also show increased relevance, e.g.,, in industries that target to ensure product quality along the supply chain (manufacturing, food, logistics) or industries that need to provide certificates to the final customer (food or lumber).

Summarizing Table 5.1, we observe higher-level properties to influence the relevance of specific benefits for different industries. Hence, research regarding a specific industry can also provide valuable insights for related industries or even those industries that only share a single common aspect. However, for every benefit and the features that blockchain technology provides, implications regarding potential challenges always have to be considered as we conclusively discuss hereinafter.

5.2 Open Challenges for a Blockchain-Enabled Industry 4.0

Blockchain technology, and especially its industrial application, is still in its infancy. In the following, we highlight the major challenges towards blockchain-based industrial processes, thereby covering technical, legal, and social aspects.

Education. A lack of knowledge and expertise is considered a major barrier for blockchain technology in industrial applications [20]. First, management bodies neither understand the technology nor the potential benefits nor arising challenges, which slows down innovation as the necessary investments are missing. Second, due to the novelty of blockchain technology, the technical departments of companies often do not fully understand the technology themselves and lack exemplary deployments for studies. Educating the various actors in the industrial sectors can thus already lead to more and better blockchain usage in the industry and speed up its deployment.

Legislature. Legal uncertainties are also a hurdle for blockchain adoption [20]. First, taxation on trades executed via cryptocurrencies is not properly regulated, which may lead to lawsuits. Second, to which extent digitally attested data, e.g., sensor data or contracts stored on blockchains, will provide evidence in a court of law remains unclear to date. Third, illegal transactions on the blockchain, e.g., those containing illicit data [78], could potentially negatively influence or harm businesses [74]. Therefore, establishing a reliable legal framework for the use of blockchain technology is crucial for the success of blockchain-supported approaches. With such a framework, courts could even directly take the role of an arbitrator for smart contracts, enabling faster and more efficient resolution of disputes [119].

Data Correctness. Blockchains ensure the immutability of stored data, but yet lack the means to verify the correctness of data submitted for inclusion. Consequently, we have noticed proposals throughout the industrial sectors that attempt to mitigate the risk of erroneous data on the blockchain. These proposals can be categorized into preemptive and reactive measures. Preemptive measures, e.g., the use of temper-resilient sensors [10, 96], attempt to prevent the upload of erroneous data in the first place. Reactive measures, e.g., using proteomics to verify the origin of wood [33], allow investigators to verify random samples or suspicious data already uploaded. If incorrect data can only be detected after insertion, businesses potentially also need ways, e.g., lawsuits or on-chain rollbacks, to handle that (automatic) decisions were executed based on wrong data. To this end, linking the provision of incorrect data to a loss of (transparently maintained) business reputation [76] holds businesses accountable for their actions. It enables a careful selection of business partners for future business relationships. Despite these countermeasures, researchers need to further investigate ways to inhibit, detect, and react to erroneous data on blockchains.

Scalability. Scalability challenges accompany the immutable, persistent, and distributed nature of blockchains. Industrial applications can generate significant amounts of data, which must be handled [71, 124]. Some applications require low-latency transactions [38], while others are less dependent on transaction latency but require a high throughput of transactions [10] or larger payloads. Correctly choosing the appropriate ledger technology and implementing scalability features (cf. Sect. 3) such as data aggregation [96, 126], off-chain storage [11, 97], block pruning [79, 81], or concepts such as side-chains [9] and sharding [129], heavily impact the applicability of blockchain technology in different industrial sectors. Hence, future research should cover the development of new scalability improvements or optimize existing approaches. Further, increasing awareness for these measures, especially their advantages and drawbacks, is inevitable for a blockchain-backed Industry 4.0.

Ledger Interoperability. Different requirements towards privacy, performance, latency, bandwidth, and smart contract complexity, may require the combined use of several different blockchains [112]. While complex business relationships cannot be realized with a single blockchain [74], e.g., companies might only want to share some sensor data publicly in contrast to publicly sharing their business relationships, the interoperability of the required ledger technologies remains challenging. Current cross-chain technologies, e.g., atomic swaps [119] and side-chains [9], still can neither transfer significant amounts of data nor link highly-specialized blockchains.

Transparency vs. Privacy Trade-offs. Initially, blockchain technology aimed to bring full transparency and decentralization to processes. However, full transparency is not always desired for industrial applications, as business secrets still have to be protected [11, 97]. Consequently, industrial use cases currently often use only permissioned and private blockchains. However, this choice limits the utility of blockchain-supported approaches, as these blockchain types often do not provide the required level of transparency for fully exploiting the benefits of blockchain technology. Modeling business processes with more fine-granular privacy control on blockchains is, therefore, an important research question. Fine-granular access control is not only important for data stored on the blockchain, but also for business logic modeled in smart contracts or related information that is stored off-chain.

6 Conclusion

The ongoing digitalization process heavily influences the industrial sector, where Industry 4.0 yields new use cases for inter-business collaborations, monitoring and exchange of sensor-based product and production information, and digitized modeling and mediation of business processes. Blockchain technology provides transparency, immutability, accountability, and a decentralized consensus for digitalized data. It thus offers significant value for the progression towards an Industry 4.0 as well as manifold individual use cases within a variety of industrial sectors. In this chapter, we analyzed the potential benefits of making blockchain technology an integral part of industrial applications, discussed challenges that industries face when adapting the technology, and surveyed case studies for heterogeneous industries from the primary, secondary, and tertiary sectors. Despite the technology's potential benefits for industrial applications, its adoption is still in its infancy, calling for further research, especially on the identified open research challenges.

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