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Blockchain – Implications and Use Cases for Additive Manufacturing

Moritz Diemer

Blockchain, the core technology behind crypto currencies such as 'Bitcoin', has been identified as a game-changing technology for almost every business function and virtually every industry (Brill et al., 2016; World Economic Forum, 2016). Properties such as immutability of data, distributed integrity, and the efficiency-enhancing potential, have put this technology on top of the agenda of management executives and researchers alike (Blechschmidt, Stöcker, 2016; Satyavolu, Sangamnerkar, 2016). Among the industries affected, additive manufacturing seems to be especially primed to profit from this technology.

Additive manufacturing (AM) technologies, more commonly known as industrial 3D printing, have been identified to be the next level concerning the industrial production of goods (Deutscher et al., 2013; Jiang et al., 2017). Efficiency-increasing potentials such as shorter time-to-market, improved designs, and the digital nature of the printing process hold significant potentials for industrial applications in aerospace, medical and dental, as well as general industrial products (Royal Academy of Engineering, 2013; Küpper et al., 2017; Cotteleer et al., 2016). However, the lack of secure data protection throughout the production process, especially when third parties are involved, is a well-acknowledged challenge that has yet to be overcome and for which so far, no efficient technological solution exists (Wee et al., 2016; Cotteleer et al., 2016; Royal Academy of Engineering, 2013).

Frankfurt School Blockchain Center
www.fs-blockchain.de
contact@fs-blockchain.de

Follow us
www.twitter.com/fsblockchain
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Frankfurt School of Finance & Management gGmbH
Adickesallee 32-34
60322 Frankfurt am Main
Germany

Blockchain technology has the potential to eliminate these challenges, by enabling the secure storage and exchange of (digital) assets, the combination of AM technology backed and secured by blockchain applications. Therefore, it is set out to bring the AM industry to the next level and thereby add to the increasing industrialization of 3D printing (Blechschmidt, Stöcker, 2016).

Therefore, this paper will enable deeper understanding and will provide an examination of the extent to which blockchain technology is applicable to the AM industry to identify use cases and fields of applications of this technology merger and to provide an overview of the startup landscape that is currently developing such use cases. Furthermore, it will critically reflect on the identified use cases with regards to implementation feasibility, making it especially attractive for researchers and practitioners alike.

Technology background

Blockchain

Since the introduction of the first crypto currency called 'Bitcoin' in 2008 by an alias named Satoshi Nakamoto, the underlying technology known as blockchain, essentially a peer-to-peer distributed ledger, has sparked the interest of various industry leaders concerning its implementation feasibility in industries and business functions (Yli-Huumo et al., 2016; Dorri et al., 2016; Nakamoto, 2008). While originally aimed at enabling the exchange of digital crypto currencies among members, blockchain technology can be leveraged for storage and transactions involving almost all kinds of digital assets (Crosby et al., 2016; Swanson, 2015). Examples for digital assets can be the right for a company's share, contracts, as well as intellectual property rights such as patents or copyrights (Holl, 2017). Consequently, and following the argument of Crosby et al. (2016), there are three basic functions a blockchain is capable of: validation of entries, the protection of entries, and the preservation of historical records.

With this in mind, there are five distinct characteristics that contribute to the promising view of blockchain technology. First, the distributed nature ensures that data stored on a blockchain is distributed among many computers. Each participant has the right to a copy of the entire blockchain and updates to a blockchain are almost instantly available to every member of the network. Secondly, each blockchain network is based on a specific consensus mechanism, thereby ensuring the validity of transactions and new entries, and removing the need for a central trust-building authority (Brill et al., 2016). The form of consensus mechanism partly depends on the openness of blockchains, respectively the use of public blockchains (i.e. open access) or private (permissioned) blockchains. Furthermore, cryptographic measures and digital signatures enforce participants to prove their identity before a transaction is validated by the network (Grewal-Carr, Marshall, 2016). The consequences of these cryptographic measures are two-fold. Firstly, once data is stored on a blockchain, its content can no longer be changed, thus acting as an important security layer (Sallaba et al., 2017). Secondly, so-called 'smart contract' applications are enabled. Smart contracts are solutions that facilitate secure and automated peer-to-peer transactions leveraging blockchain technology and coding (Yli-Huumo et al., 2016; Sallaba et al., 2017). These automated transactions require further security elements to enable traceability and verification. Therefore, another important security characteristic to all blockchains is the time-stamp logic for every block created and added to the blockchain (Grewal-Carr, 2016).

Given the novelty of blockchain technology in industrial applications, there are important challenges to overcome. Obstacles such as limited scalability, security issues (especially with smart contracts), and missing regulation and governance need to be addressed by the interested parties. Nevertheless, and despite these challenges and obstacles, important positive developments such as the further growth of the Enterprise Ethereum Alliance and the steadily increasing number of blockchain startups that deal with an increasing amount of use cases in different industries could be realized recently.

Additive manufacturing

Out of these industries, the AM industry has been given special attention regarding blockchain applicability (Metal AM, 2016; Young, 2016; Stevenson, 2016). AM technologies, have been first established in the 1980s and were at the beginning mainly used for rapid prototyping, thus accounting for the decreasing development cycles for new products (Gu, 2015; Royal Academy of Engineering, 2013). Based on the efficiency-enhancing potentials regarding prototype development, early adopters of AM technologies were, therefore, industries such as aerospace and automotive development centers (Deutscher et al., 2013; Gibson et al., 2015). The current increasing industrialization of AM is underlined by looking at the impressive growth figures. According to an analysis by the Boston Consulting Group in 2017, the AM market is growing '[…] at a compound annual growth rate (CAGR) of almost 30% until 2020, achieving a greater than threefold increase in size.' (Küpper et al., 2017, p. 2; Wolfgang et al., 2017). Furthermore, the increasing adoption and future potential of AM technologies is confirmed by the Royal Academy of Engineering (2013), which depicts the increasing industrialization of AM, by highlighting its growing use to produce final products in the areas of aerospace, industrial goods, automotive, and medical and dental (Zistl, 2014; Möller, Durand, 2015).

Alongside benefits such as less material waste and the use of innovative materials, the digital nature of AM puts these manufacturing technologies in a strong position to support superordinate trends such as digitization and Industry 4.0.

But, besides challenges such as limited scalability and high costs, the digital nature of AM processes triggers significant data protection concerns and signifies IP-related threats to companies. Based on the digital nature of AM and the ensuing various (data) interfaces, two points of views have to be considered: data and intellectual property protection within the manufacturing process and data and IP management within the AM value chain and across organizational boundaries. Therefore, given the importance of data and IP protection in AM, researchers identify blockchain as a possible solution to these data-related threats and through this, enable further and more rapid industrialization of AM (Blechschmidt, Stöcker, 2016; Trouton et al., 2016).

Blockchain and additive manufacturing

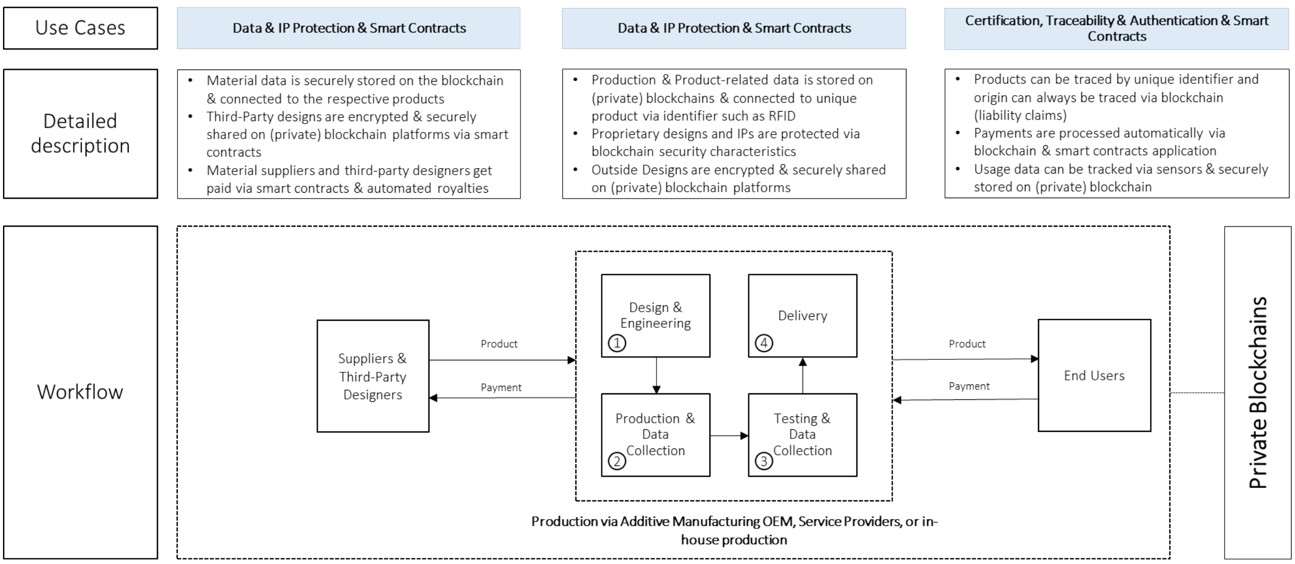
To verify these potentials and possible fields of application of blockchain and AM, several semi-structured interviews with experts were held and a complementary structured literature review was performed. Through this, four use cases in which blockchain technology could be implemented in AM were identified: Data & IP protection, traceability, authentication and certification, smart contracts, and process automation.

The use cases data & IP protection, traceability, authentication and certification, smart contracts, and process automation have been identified for blockchain applications.

The proximity to real-life implementation of the use cases differs significantly. Before going into detail on the identified use cases, Figure 1 depicts how a blockchain-enabled AM value chain could look like.

Figure 1

Blockchain-enabled additive manufacturing framework



Source: Trouton, Vitale, Killmeyer (2016), Blechschmidt, Stöcker (2016), and own illustration.

Combining the above-mentioned use cases, the implementation of blockchain technology can, therefore, lead to a more secure, efficient, and reliable

AM process and value chain that is depicted in a blockchain-enabled AM framework.

The implementation of blockchain technology can lead to a more secure, efficient, and reliable additive manufacturing process and value chain.

Consequently, the framework reveals instances in which blockchain technology can be integrated as a security and exchange layer in AM. While product- and production-related data can be stored as transactions on (private) blockchains for increased security, in-house quality assurance and traceability, the interviews and the complementary literature review revealed that especially in cross-organizational settings, the introduction of blockchain is expected to be particularly beneficial. To shed more light into this aspect, the following paragraph will provide more details about the identified use cases with a specific focus on implementation proximity and feasibility.

Use cases

Data and IP protection

With 36 articles mentioning this use case and 43 citations from the semi-structured interviews for this field of application, the use case of protecting sensitive data and IP, and especially to secure 3D printing and design files (and the ensuing printing parameters), emerges to be highly important and close to implementation. For instance, Allison (2016) notes that first proof-of-concepts have been successfully executed and the protection of intellectual property rights will pave the way for new (additive) manufacturing processes and increase efficiency. Furthermore, many interview partners suggested that blockchain technology is exactly the technological solution that has been missing in AM concerning the protection of sensitive data and IP. Within this use case, two areas of application could have been identified:

firstly, the mere secure storage of data and IP. Secondly, through the use of smart contracts (see below), IP could be securely and automatically shared without the risk of malicious behavior and losing control over own sensible data. The secure and automated sharing of sensible data, and especially of 3D printing files (including the necessary printing parameters), can then lead the way to a more efficient collaboration among organizations and to new business models.

Traceability, authentication, and certification

The second use case, as noted in the reviewed literature and by the interview partners, is made possible through the characteristics security (immutability) and distribution of blockchains, efficient part traceability, authentication, and certification (Metal AM, 2016; Stevenson, 2016; IBM, 2016; Holl, 2017; Young, 2016; Sawtooth Lake, 2017). As mirrored by the number of coded citations from the interviews and the literature review, part verification and proof of (material) provenance are thus also key blockchain use cases, specifically relevant in the AM industry. The usefulness of this field of application is further underlined by Holl (2017), who notes that 'Using blockchain technology as a shared database with suppliers could help track the quality and compliance of products along the entire supply chain'. Keeping in mind the major industries to profit from AM technologies, namely aerospace, automotive, as well as medical and dental, the need for part verification and traceability becomes even more evident (Holl, 2017; Young, 2016). Apart from the use cases traceability and authentication of blockchain technology within the AM industry, findings from the interviews further revealed one more instance that is closely related to the above. As most additive manufactured parts require certification and quality assurance by third party service providers such as the TÜV, the implementation of blockchain could greatly facilitate these certification efforts (Blechschmidt, Stöcker, 2016; Bahga, Madisetti, 2016).

Smart contracts

With 29 citations for this use case within the interviews, smart contracts should be, quantitatively speaking, seen as less important compared to the first two use cases outlined above. However, by looking closer at the actual citations and as for example mentioned by one interview partner, smart contracts in AM are the basic mechanism with which other use cases of blockchain in AM are made possible and were thus identified as a separate entity for this article[1]. Consequently, especially given the results of the interviews, there are three instances in which the use of smart contracts is regarded as auspicious and thus worth further detailing. First, the secure sharing of IP and 3D printing files including automated royalty payments. Secondly, blockchain-enabled licensing management. Lastly, smart contracts enable the secure and automated governance of business processes in AM. Leveraging the escrow-functionality of blockchains and smart contracts, such processes can, for example, include the order fulfillment and processing. Nevertheless, it proves difficult to determine the exact impact and probability of the introduction of smart contracts within AM. Leveraging the findings of Blechschmidt and Stöcker (2016) and from the interviews, important unsolved obstacles contributing to the uncertainty regarding smart contracts are the lack of integration into the current software environment, the low technical maturity of smart contracts, as well as the unsettled legal status and enforceability of smart contracts.

Process automation

According to the literature, in the distant future, blockchain technology, including smart contracts, has the potential to eventually enable machine-to-machine communication and thereby automate complete business processes in the 3D printing industry. Blechschmidt and Stöcker (2016) outlined in their paper the concept of a shared autonomous factory model. In this decentralized model, blockchain and smart contracts enable a more efficient printing of parts as printers actively seek to find print jobs that fit their technical features and that need to be printed at a specific location (Blechschmidt, Stöcker, 2016; Satyavolu, Sangamnerkar, 2016; Bahga, Madisetti, 2016). Additional advantages of this decentralized manufacturing approach of additive parts include the decrease in necessary inventory, lower transaction costs, and shorter supply chains (Bahga, Madisetti, 2016; Blechschmidt, Stöcker, 2016). Therefore, by replicating the entire AM value chain and production process on a blockchain, researchers and experts alike aspire to empower a more transparent, efficient, automated, and secure form of AM (Trouton et al., 2016; Blechschmidt, Stöcker, 2016; Bahga, Madisetti, 2016). Nevertheless, given the long stretch predicted for this use case to gain traction, implementation efforts and proof-of-concepts are still very rare (Stöcker, 2017).

Startup landscape

For the operationalization of the above-identified use cases (see Figure 2), there is a small startup scene working on proof-of-concepts for blockchain technology in AM.

Figure 2

Blockchain angels, venture radar, CB insights, web search, and own illustration

	Name	Use Case & Solution	Industries & Application	Implementation Status	Country
1	CubiChain Technologies	• Data & IP Protection • Traceability & Authentication	• Aerospace • Automotive	• Proof-of-Concept	USA
2	3D Plex	• Data & IP Protection	• n.a.	• n.a.	USA
3	3dTrust	• Data & IP Protection • Traceability • Process automation	• Aerospace (e.g. military)	• Proof-of-Concept • Patented technology	Germany
4	Projekt SAMPL	• Data & IP Protection • License management	• Industry applications	• Proof-of-Concept	Germany
5	Genesis of Things	• Traceability • Smart Contracts • Process automation	• Airline industry • Industry applications	• Proof-of-Concept	Germany
6	Creative Barcode	• Data & IP Protection	• Design rights for consumer goods	• Live	United Kingdom

Sources: Company websites and databases.

The overview of startups required investigation of several databases and company websites. Through this, a total of six startups and initiatives were identified as working on blockchain applications with a specific focus on AM. The use cases that are being developed by the startup scene of blockchain in AM reflect and reinforce the findings from the interviews and the structured literature review.

Not only do they generally work on the same use cases, but also the distribution (i.e. the current importance) of the fields of applications ties together with the findings from the previous chapters.

Consequently, the majority of startups is working on using blockchain technology to protect sensitive data and IP. Further, several startups are also developing blockchain-based applications to enable a seamless stream of information for additive manufactured parts (Stevenson, 2016; Blechschmidt, Stöcker, 2016). Furthermore, a small number of startups is working on smart contract applications for the AM industry.

Blockchain-enabled business models in AM

Moreover, researchers and practitioners believe that the introduction of blockchain technology can pave the way for new business models within the AM industry.

The emergence of such innovative business models in the 3D printing industry is made possible by two unique features of blockchains: first, the ability to integrate smart contracts and thereby automate business operations upon certain conditions. Secondly, leveraging the trust-building and security abilities of blockchains and thereby eliminate the need for trusted intermediaries, even when (unknown) third parties are involved, blockchain breaks ground for a more distributed value creation and secure peer-to-peer transactions.

Researchers believe that the introduction of blockchain technology can pave the way for new business models within the AM industry.

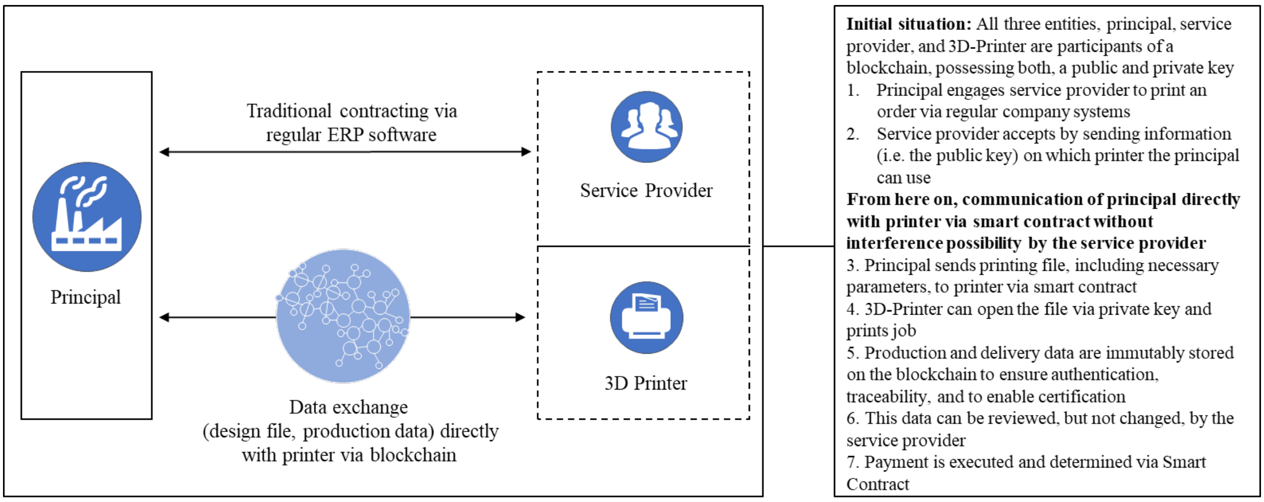
Thus, there are specific new business models thinkable at this moment. First, designers and engineers of 3D print files (and the ensuing necessary printing parameters) could securely offer and share their designs via blockchain-based marketplaces. This would ensure that the owner of such designs can define the quantity, time, price, and other conditions to which the respective design is available and to whom it is available.

Moreover, end users of additive manufactured parts could securely outsource the printing activities without risking a loss of control on their data and products.

In this so-called ‘peer-to-machine’ business model (see Figure 3), contracts between a principal and an agent are settled via regular ERP systems, while the data and files required for the printing of the part(s) are solely shared via blockchain and smart contracts directly between the principal and the printer. By equipping each participating party with a unique public and private key and through the use of smart contracts, the security and automation of the production process as well as product traceability during and after the printing process are increased.

Figure 3

Peer-to-Machine Blockchain Additive Manufacturing Framework



Source: Ackermann, Diemer, Dill (2017) and own illustration.

In summary, the above-mentioned blockchain-based business models (processes) hold several advantages. Factors, such as a reduced risk of IP infringement, lower transaction costs, and shorter time to market thus put this technology merger in a promising position for future applicability. Nevertheless, so far, there is a very limited number of proof-of-concepts and real-life implementation of blockchain technology within AM.

Therefore, the next chapter will evaluate the findings of this paper with a specific focus on implementation suitability and feasibility and thereby provide the reader managerial implications of these findings. Finally, a short outlook is provided.

Evaluation and managerial implications

Benefits and challenges

Figure 4 displays blockchain's high potential to add value to the further industrialization of AM, especially in the fields of data and IP protection, as well as traceability, authentication, and certification (Trouton et al., 2016; Bahga, Madisetti, 2016; Schlatt et al., 2016; Blechschmidt, Stöcker, 2016). Thus, it can be stated that indeed the first two use cases perfectly fit not only the characteristics of blockchain but furthermore alleviate the needs and challenges of the AM industry. Especially the blockchain characteristics security, distribution, and cryptography will enable these use cases and thereby make the AM industry more efficient and data secure. Consequently, these characteristics and the ensuing use cases will promote the further industrialization of AM, particularly by lowering the risks of IP infringement and by facilitating product traceability and authentication throughout the AM value chain. Especially for the use cases smart contracts and process automation are some critical challenges that need further attention.

Figure 4

Use case evaluation

Blockchain Characteristic	Impact Organization & Processes	Applicability to Use Cases	Benefits for Additive Manufacturing
Distributed	• Shared among participants • Enables trust without intermediary • Distributed verification process ensures validity and reliability of data	• Data & IP Protection • Traceability, Authentication, and Certification	• Efficient & secure data management for organizations • Increase efficiency & security in AM value chains • Enablement of new business models
Consensus-mechanisms	• Distributed verification process ensured • Secure data integrity	• Data & IP Protection • Traceability, Authentication, and Certification	• Efficient & secure data management for organizations • Increase efficiency & security in AM value chains
Cryptographic measures	• Risk reduction • Automation of transactions and processes	• Data & IP Protection • Traceability, Authentication, and Certification • Smart Contracts	• Risk reduction • Automation of processes • Enablement of new business models
Programmable logic	• Enforcement of transaction criteria • Automation of transactions and processes	• Smart Contracts • Process automation	• Automation of processes • Increase security & efficiency of AM industry • Enablement of new business models
Security	• Time-stamp logic	• Data & IP Protection • Smart Contracts	• Secure data management in AM value chains and organizations

Source: Own illustration.

Concerning the technological aspects, notably, two challenges and risks prevent further and more rapid adoption of blockchain technology within the 3D printing industry. First, missing and faulty integration of blockchain applications into the existing software environment. Secondly, albeit offering vast potentials and opportunities, smart contract use cases and applications are subject to vulnerabilities and loopholes (Furlonger, Valdes, 2017; Blechschmidt, Stöcker, 2017; Bahga, Madisetti, 2016; Christidis, Devetsikiotis, 2016). From an organizational point of view, especially the missing expertise and know-how is a significant challenge for enterprises. Additionally, most organizations take on a passive role instead of a more proactive role to implement blockchain into their processes. Legally, missing governance and regulation is a severe impediment for more rapid adoption of blockchain technology and especially smart contracts.

In summary, and despite these challenges, industry experts and researchers agree on the possible promising merger of blockchain technology and AM. Specifically, the protection of sensitive data and IP seems to be the most promising use case. Process automation enabled through smart contracts is yet feasible. As the AM industry is looking for innovative ways and technologies to make the production process more reliable and data more secure, blockchain technology holds significant potentials that are worth further exploration.

Managerial implications

Unlike in other industries and business functions, the core business in AM is not at risk due to the rise of blockchain. Rather, in AM, the introduction of blockchain can unleash untapped efficiency and automation potentials that enable and expedite further industrialization of AM.

Thus, enabled through the extensive overview of blockchain use cases in AM, practitioners need to critically reflect on the usability of these, as blockchain does not provide a one-size-fits-all solution for AM.

Large organizations can choose from a variety of strategic options such as in-house development, startup acquisition, and partnerships. SMEs should make use of outside knowledge (i.e. in the form of so-called 'Hackathons' or partnerships) to get in touch with blockchain technology and gain competitive advantages.

Despite enormous efficiency potentials, a clear-cut picture on future developments of blockchain in AM cannot be given at this stage. This is especially due to the extreme novelty of this technology merger and with regards to the outstanding challenges. However, given the promising potentials, practitioners should familiarize themselves with this new technology and thereby drive further understanding and implementation of blockchain applications in AM.

If you like this article, we would be happy if you forward it to your colleagues or share it on social networks.

Moritz Diemer is a Ph.D. Candidate and Research Assistant at The Julius Maximilians University of Würzburg. You can contact him via LinkedIn (https://www.linkedin.com/in/moritz-diemer-52728b11a/).

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[1] Smart contracts are thus generally also applicable to other industries and business functions.