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Cambridge BMI Group Working Papers

Cambridge BMI Group Working Papers: 02/2020

DOES BLOCKCHAIN FOR 3D PRINTING OFFER OPPORTUNITIES FOR BUSINESS MODEL INNOVATION?

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Overview: Blockchain combined with 3D printing offers businesses untapped opportunities. Blockchain can help businesses overcome intellectual property and data security barriers, allowing them to take advantage of emerging 3D printing business models. Specifically, blockchain can facilitate local manufacturing and may lay the groundwork for new business models like industrial design marketplaces and shared factories. Businesses could also improve their value proposition by offering additional services around a printed part, improving value delivery, and offering less costly and more customized products that involve fewer risks. Blockchain could transform the way firms create, deliver, and capture value in 3D printing ecosystems.

Keywords: Blockchain, 3D printing, Additive manufacturing, Business model innovation

Does Blockchain for 3D Printing Offer Opportunities for Business Model Innovation?

Blockchain use in financial services, global trade, and supply chain management has received significant attention in the last five years, whereas interest in blockchain for 3D printing remains limited. The low level of interest is not surprising given the fact that other manufacturing processes are much more mature than 3D printing. At the same time, the limited interest is surprising since the recent adoption of distributed (interorganizational) 3D printing has fuelled discussions about intellectual property (IP) and secure data management while other production processes have not (Kurfess and Cass 2014; Yampolskiy et al. 2018).

3D printing has emerged as an important technology for parts production, but most businesses have not yet taken full advantage of its potential. In the wake of emerging distributed manufacturing principles, 3D printing offers far-reaching opportunities for attractive business models, which thus far are inhibited by IP and data security concerns. In this article, we show how blockchain might address these issues and leverage promising business models for the 3D printing ecosystem.

3D Printing's Exponential Growth

With an estimated total market volume of $15.8 billion for 2020 and an anticipated growth rate of more than 100 percent until 2024 (Wohlers Associates 2019), 3D printing has attracted a lot of attention from managers and researchers. Recent examples of printed bridges, houses, and e-vehicle parts (Marr 2018) indicate that the technology is no longer only suited for rapid prototyping or niches such as dental implants or lightweight aerospace parts (Petrick and Simpson 2013)—3D printing is moving to critical mass (Forger 2019).

The drivers for 3D printing's rapid development are twofold. Engineers are gradually dismantling technical 3D printing barriers such as surface quality and fabrication speed. In addition, firms are starting to realize 3D printing's significant potential to transform their existing business models (D'Aveni 2018). For instance, 3D printing could change the way firms create value by making it easier to integrate customers into product design, thereby enabling co-creation and mass customization. Furthermore, local on-demand printing possibilities would open new paths for value delivery. Although researchers have already proposed several of these possibilities (Bogers, Hadar, and Bilberg 2016; Durach, Kurpjuweit, and Wagner 2017), businesses have not capitalized on these opportunities. Instead, most firms use 3D printing exactly as they have used traditional manufacturing processes for decades, without modifying their underlying business models. Although solely substituting traditional manufacturing processes with 3D printing allows for the production of smaller batches of more complex geometries, it does not radically change how these firms conduct business.

We argue that firms have not taken advantage of these business model opportunities because they require firms to use 3D printing on an interorganizational level, which necessitates the exchange of sensitive information such as construction plans, 3D designs, and material specifications. Doing so may expose firms' IP to external parties and create vulnerabilities, including unauthorized use of IP, counterfeiting, and malicious data manipulation. The design files, which comprise the lion's share of value creation, are highly valuable assets that cannot be sufficiently protected by traditional means, such as design and utility patents, trademarks, or copyright (Kurfess and Cass 2014).

Blockchain is the most prominent form of distributed ledger technologies, which are "databases that are massively replicated on all the 'nodes' or machines in the system" (Babich and Hilary 2020, p. 224). Blockchain can alleviate some of 3D printing's major limitations regarding IP and data security (Kurpjuweit et al. 2020). For instance, the replication of sensitive 3D printing file and process data across the blockchain network makes the integrity of this data non-repudiable, and therefore easy to uncover potential data tampering. Some firms have already recognized the potential of integrating blockchain with 3D printing and have launched large consortia projects to test how this combination could translate into business value. Since little is currently known about this potentially disruptive use of blockchain technology, our objective is to explore how these blockchain platforms work and what kinds of opportunities blockchain creates for innovating business models in the 3D printing ecosystem.

The Case Study

This case study is part of a larger research project investigating the emerging use case of blockchain platforms for the 3D printing ecosystem (Kurpjuweit et al. 2020). All stakeholders involved in the 3D printing value chain make up the 3D printing ecosystem. We focus on the business model opportunities arising from integrating blockchain and 3D printing. We studied three ongoing consortia projects, Alpha, Beta, and Gamma, that are developing individual blockchain-based platforms for 3D printing. A platform is the digital solution each consortia project is developing based on a blockchain infrastructure.

Project Alpha is a consortia project comprising organizations and institutions from various backgrounds. A medium-sized product lifecycle management software company leads the project; the goal is to develop a blockchain platform for industrial 3D printing applications (for example, for the automotive industry or aircraft construction). Other project partners include 3D printing and blockchain startups, a firm from the semiconductor industry, academic institutions (two universities and one research institute), and a law firm. Collectively, Project Alpha is leveraging blockchain technology to build a digital platform that unites several actors along the 3D printing value chain. Project Alpha's primary objective is the development of a blockchain-based licensing system for the secure distribution of 3D printing files. Project Alpha collaborates with potential platform users from the aviation and automotive sectors to test blockchain-based 3D printing data transfer with their suppliers and customers.

Like Project Alpha, Project Beta is a large consortia project that includes partners from startups (blockchain and 3D printing), academia, and industry (software development, automotive, energy, and banking). Similarly, Project Beta aims to develop a blockchain-based platform for 3D printing—it has already completed successful pilots with printed prototypes. Multiple members of Project Beta are actively exploring business model opportunities for 3D printing using their blockchain platform.

Compared to Projects Alpha and Beta, Project Gamma is a smaller project initiated by a 3D printing startup and a university. Its focus is on 3D printing products for end customers, and it aims to leverage blockchain technology to safeguard the distribution of 3D printing design files. Project Gamma's vision is to create a platform solution where printing capacities from multiple actors can be exchanged dynamically and on-demand. In this scenario, blockchain serves as the infrastructural foundation of Project Gamma's platform.

Method

We identified Projects Alpha, Beta, and Gamma through an initial phase of desk research, which entailed mapping involved institutions and searching for potential points of contact. We contacted the project leaders, explained our research context, and asked for an interview. To find additional participants to interview and gather further insights, we also attended blockchain and 3D printing conferences (we called the experts sourced through this approach "external 3D printing experts" or "external blockchain experts") (Table 1). We interviewed 14 experts for approximately one hour each; we focused primarily on the projects' objectives, problems in the 3D printing workflow that the projects aim to address using blockchain technology, and (potentially) emerging 3D printing business models based on blockchain platforms.

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We iteratively collected and analyzed the interview data and adjusted the semi-structured interview protocol as the research proceeded (Patton 2015). We recorded the interviews, took notes, and created memos immediately after each interview to capture our first impressions (Miles and Huberman 1994). Then we coded the transcribed interviews and analyzed the transcripts inductively to identify patterns (themes) across the interviews, which reflected our key areas of interest. These themes included the project description and objectives, 3D printing limitations addressed by blockchain, and emerging business models. For each interview, we followed the interviewee's terminology and understanding of business models. During the analysis, we aggregated textually congruent concepts (such as business models) under corresponding themes, ensuring a consistent terminology. To validate this process, we sent each interviewee an aggregated summary of their interview. We had follow-up emails with some interviewees to clarify terminology.

We complemented our interview data by collecting publicly available archival data about the analyzed projects (newspaper articles, blog posts, industry reports, and white papers), which collectively contributed to a holistic overview of the projects.

Key Issues of Distributed 3D Printing

Our findings suggest three key issues inhibit the emergence of distributed 3D printing business models: the unauthorized use of IP (specifically, computer-aided design (CAD) file usage without license), counterfeiting (pirated product copies), and malicious data manipulation (tampering with design files or process data). Regarding unauthorized IP usage, one expert from Project Alpha said, "When using 3D printing technologies, it feels like everyone—given that he has the relevant data—is able to reprint a specific part. That's exactly why we need to focus on copyright protection." Since most development effort and value is embedded in the digital 3D CAD files, illegitimate reprinting activities pose substantial financial threats for firms using 3D printing. Another interviewee working on Project Alpha expressed concerns about increased risks of product counterfeiting: "How to handle the case of 3D printing? If I have the ability to produce something that looks and works exactly like the original, wouldn't this result in a proliferation of counterfeit, imitation, and pirated copies?"

Technical improvements and decreasing costs for printers and 3D scanners reinforce the risk of counterfeit products. These developments will make the IP issue the prevalent discussion in the field of 3D printing. Simultaneously, existing laws cannot prevent the use of counterfeit products (Kurfess and Cass 2014). One potential consequence of counterfeit products in the supply chain is product failures that may cause injuries or even fatalities (Kurfess and Cass 2014).

The digital nature of 3D printing creates potentially serious threats in the form of malicious data manipulation (Yampolskiy et al. 2018). Unauthorized parties could manipulate or misuse the high-value design data manifested in CAD files, as well as sensitive processing, simulation, or testing data—these risks are especially dangerous when 3D printing is used interorganizationally because sensitive data must be transferred beyond a firm's boundaries. For example, imagine an aircraft original equipment manufacturer (OEM) sending the design file for a spare part to a local maintenance, repair, and overhaul provider for printing at the point of demand (Wagner and Walton 2016). Here, the potential threats include inadequate IP management—for example, the originator sending its IP in its design file, which means it could be replicable by anyone outside the firm —and design tampering that could occur during the time between transferring the design file and the actual printing. The real-life manipulation of a hacked drone CAD file that caused the drone to crash a few minutes after take-off demonstrates the gravity of this threat (Belikovetsky et al. 2017).

As one Project Alpha interviewee said succinctly, "We have so many opportunities on a technical level. But all these opportunities are increasingly limited due to poor data security that can't keep hackers from getting in." As our data show, firms considering distributed 3D printing face substantial IP and data threats. Countering these threats will be key for these firms to successfully leverage more open 3D business models.

How Blockchain May Help

The 3D printing value chain requires effective security mechanisms to protect against IP and data security threats. According to our interviewees, blockchain technology, which can protect data records against manipulation, could serve as an underlying safeguarding layer in the 3D printing value chain. A Project Beta interviewee said, "The benefits that 3D printing offers also create certain risks. If we make our whole supply chain more distributed, we have to open our organization even more. It might be the case that we pass on sensitive data to people we do not fully trust. And at this point, blockchain helps to make 3D printing safer."

A blockchain-based platform requires digital input data. Compared to other cases of blockchain use (for example, Maersk and IBM's global trade platform, diamond tracking, food traceability), the most important input data in the 3D printing ecosystem—design files and production process data—are already digitally encapsulated (Holmström et al. 2019). In contrast to more conventional projection processes, 3D printing already relies on a digital process chain, which can thereby facilitate blockchain adoption (because it also requires digital input data). In essence, multiple aspects of the 3D printing process chain do not require digitalization because they're digitized already. Accordingly, bridging the 3D printing process and the digital ledger is both practical and feasible. The Project Beta leader explained the selection of the 3D printing use case: "Blockchain is really important for manufacturing and supply chain management. Hence, we intensively looked into 3D printing. We particularly searched for simple yet important use cases. . . . And seemingly simple is the case of 3D printing, because there we already have a *digital* process chain."

At the same time, the manufacturing ecosystem changes from centralized, economies of scale-driven manufacturing to open, distributed manufacturing networks, resulting in more interorganizational cooperation and data sharing (Ben-Ner and Siemsen 2017; Holmström et al. 2019). 3D printing is a key technology within this paradigm shift in the manufacturing ecosystem—it is expected to unfold its business model potentials (for example, local on-demand manufacturing) in precisely these interorganizational settings. Blockchain, as a distributed ledger technology, matches these features with its particular strength in networks involving multiple stakeholders. One Project Alpha expert explained the 3D printing setting: "We have an environment including multiple stakeholders: designers, copyright holders, OEMs, printing service providers, and maintenance operators that need printed spare parts. And these stakeholders do not necessarily trust each other. Of course, they are able to and will establish contractual relationships, but they need possibilities of protection in order to run their business models securely and smoothly. And in a setting of several actors, with mandatory peer-to-peer communication, blockchain is a solution." The inadequacy of IP and data security structures hampers 3D printing business model opportunities that emerge from the encapsulation of product design and production process data—which allow for greater independence, customization, organizational and geographic redistribution, localization, or interactivity of design and manufacturing processes (Petrick and Simpson 2013; Bogers, Hadar, and Bilberg 2016; Holmström et al. 2019).

How can blockchain *technically* help to create this secure environment that is crucial for distributed 3D printing business models? The three projects we studied follow the fundamental idea of mapping the lifecycle of a 3D printed part, involving all relevant stakeholders and corresponding workflows, on the blockchain. These stakeholders range from material suppliers, 3D printing service providers, OEMs, and logistics service providers, to final customers. Beyond these stakeholders involved in the physical flow of parts, other complementary actors primarily address the information flow and could include external originators uploading their designs to the platforms, certification authorities, or regulators and financial institutions (for payments, financing, or insurance) (Figure 1).

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During our study, Project Alpha had already implemented a blockchain-based licensing system, enabling the secure distribution of printing licenses across a network of external printing service providers. Project Beta, which focuses on streamlining 3D printing workflows, such as blockchain-based certification and authentication of 3D printed parts, had already run successful pilot projects with printed prototypes that could be authenticated via blockchain. Midway through our study, both Project Alpha and Project Beta aimed to connect more 3D printing stakeholders to their platforms, gradually increasing the number of workflows mapped on the blockchain. Project Gamma was laying the groundwork for a 3D printing network where printing capacities can be dynamically exchanged via a blockchain-based platform.

During the analysis period of this study, the three projects deployed permissioned blockchain solutions as an underlying infrastructure for their platforms, meaning that consortia members (stakeholders serving as blockchain nodes) are known and pre-selected. Although the interviewees could not specify a predefined timeline, all three projects plan to move towards more open (public) solutions—in a later stage of technological maturity—to leverage network effects.

The blockchain safeguards and shares part-related data, especially printing licenses, production process data, material provenance, test and simulation data, payment records, and part certifications. Feeding these data into a secure blockchain platform facilitates 3D printing business model opportunities.

Emerging Business Model Opportunities

Bogers, Hadar, and Bilberg (2016, p. 227) wrote, "While new technologies can sometimes be implemented with existing business models, AM [additive manufacturing] technologies are disruptive to the extent that they may require some reshaping or reinvention of the business model in order to capture its value." Additive manufacturing is the umbrella term for 3D printing and other production processes. A business model is the architecture of a business, which defines how customer value and payment are generated and ultimately turned into profit (Teece 2010). This definition implicitly mentions value proposition, value creation, and value capture, all of which are key elements of any business model (Dyer, Singh, and Hesterly, 2018; Velu 2016). The value proposition is the complete bundle of products/services offered to a customer and explains why a customer chooses one company's offering over that of another (Osterwalder and Pigneur 2010). While value creation corresponds to the economic activity of generating new value for customers, value capture identifies the ways in which value can be monetized and retained.

Since we study business model innovation in the interorganizational context of blockchain platforms for 3D printing, we added a fourth element, *the value network,* which describes how firms connect with external parties (customers, suppliers, partners, distribution channels) to complement their internal resources (Velu 2016). Business model innovation can occur when there are changes in these elements or their interdependencies, leading to a new market or new opportunities in an existing market (Amit and Zott 2012).

Our findings show how blockchain in 3D printing can shape each of these four business model elements, facilitating business model innovation (Table 2). Three major potentials for business model innovation emerged from our interview data: local manufacturing, shared factories, and secure design marketplaces.

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Local Manufacturing

Experts suggest 3D printing will redistribute and localize manufacturing (Durach, Kurpjuweit, and Wagner 2017; Holmström et al. 2019). However, our data suggest that insufficient IP and data protection mechanisms often impede this business model. In a scenario where businesses outsource 3D printing activities to local service providers—where the roles of CAD file originators and actual part producers diverge—the secure handling of IP and data transfers needs to be guaranteed. To address this issue, Project Alpha developed a blockchain-based license management system. One of the project co-founders explained the idea: "When the printing process is completed, a process data file is automatically created. This file will be hashed and the hash value will be stored on the blockchain. Then, this data file will be linked to a license and I will be able to see that this license was used to print exactly this part with exactly these process parameters. All this is stored [on the blockchain]."

The receiving printer has a semiconductor chip (a *secure element*) containing a unique private key it uses for authentication. By creating a blockchain transaction, the file sender provides a license, including the maximum number of allowed printings. A physical printing process triggers the use of one license, thus reducing the smart contract-based license count by one. To ensure data integrity, a unique fingerprint called a hash value of the developed design file is immutably stored on the blockchain. Before the printing process, the received file is automatically hashed again—that is, it receives another unique fingerprint. A comparison of both hash values can reveal changes in the file and identify potential data manipulation attempts.

Being able to transfer sensitive design files securely might spur the development of distributed manufacturing networks. As a Project Beta employee explained, "If there are secure process chains. . . this is a strong enabler for secure decentralized 3D printing." Another Project Beta interviewee said, "Is Airbus able to set up its own print service at hundreds of airports worldwide? Probably not. But what we could see is that there are different 3D printing service providers emerging and then working together with Airbus. Airbus then tells them: 'Print this part with the following specifications for this specific customer.' This means that there will be far more supply chain partners in the future." However, secure IP and data management might not be sufficient to run sustainable business models for applications at industrial scale. For example, Airbus would need to evaluate further whether each service provider has printed according to the correct parameters and specifications such as speed, material, temperature (Wagner and Walton 2016). Furthermore, the end customer may want to verify the printed part's authenticity.

Currently, proving compliance often occurs using paper-based certifications, regular audits, and the building of trusted relationships with suppliers. The blockchain projects we studied are working to integrate printing process data such as machine parameters, actual fabrication data, quality and simulation tests, and certifications into the blockchain. Storing these (and other part-related) data on the blockchain could eventually amount to a digital representation of the physical object, referred to as a digital twin (Schleich et al. 2017). This immutable record would ensure streamlined compliance processes and increased efficiency, resulting in altered cost structures.

The blockchain protocol would serve as an infrastructural layer, safeguarding each part's digital record and creating a platform for all part-related lifecycle data. Today, different stakeholders create different records, measure different parameters, and store these data in their own databases, which often results in silos. In contrast, blockchain allows every network participant to access an identical copy of the same data, which decreases information asymmetries and coordination costs by creating a single source of truth, a non-repudiable state of information that ensures data integrity.

To unlock these possibilities, tamper-proof bridging between the physical world (the printed part) and its corresponding digital world (the blockchain record) is crucial. Thus, Project Alpha and Project Beta developed tagging solutions using radio-frequency identification (RFID) technology. A Project Alpha employee we interviewed said, "What is very exciting about 3D printing is that sensor technology, for example, RFID chips can be printed into products, bridging the digital and the physical world. . . . That enables intellectual property rights tracking and protection that you do not have with conventional technologies. So far, I could only glue a seal on a product, but that seal can be forged. Apart from that, I don't have a register where everyone can check whether the seal is valuable at all."

With such an RFID tag, stakeholders in the 3D value chain can access the digital memory of the printed part. This capability is appealing, for example, for an aerospace or medical company's risk management function that buys sensitive components and wants to verify the part's authenticity, production process parameters, and certifications. It's also appealing for creators of 3D design data looking to retrace license usage from local manufacturers.

Beyond industrial distributed 3D printing, home manufacturing, where end users print parts from their desktop printers at home, is an often discussed but as yet unrealized scenario. Consumers as producers is not new. Back in the 1980s, Alvin Toffler created and popularized the concept of the *prosumer*, which has not only created a rich body of academic literature but has become an integral element for business models in numerous service industries (Toffler 1980). Many scholars praise 3D printing as the technology that brings the prosumer concept to manufacturing (Bogers, Hadar, and Bilberg 2016). Actual adoption rates, however, have not keep pace with the optimistic predictions. Some experts are confident that blockchain-based 3D printing platforms could help to resolve major barriers to adoption and make this home manufacturing scenario more realistic. A Project Gamma interviewee said, "The idea is that you are no longer a customer, you are a prosumer. The things you produce are what you consume. So, the idea is that instead of a company that produces what you need, you do it by yourself and you pay only when you access the knowledge, in the form of the design. So, to track this process, blockchain is helpful. Because you only pay when you print and you print only what you pay for."

More distributed manufacturing networks would slash warehousing and transportation costs, as firms would be able to outsource the printing process to the location of demand (to local service providers or customers), translating fixed costs to variable costs. Beyond improving their value proposition through better value delivery, this optimized cost structure and reduced transaction costs would help manufacturers capture more value (Schmidt and Wagner 2019).

Shared Factories

Our interviewees described a future scenario, which we call *shared factories*, that extends the opportunities of local manufacturing. Following the sharing economy paradigm, firms could offer and monetize their own unused printing capacity to other firms—shared factories would enable firms to flexibly trade production capacities on an interorganizational level, significantly increasing capacity utilization (Kurpjuweit et al. 2020). Beyond offering own-printing capacities, firms could access the capacities of multiple 3D printing providers competing in a global marketplace, which would lead to increased flexibility, more local production, and more agile supply chains that are less vulnerable to disruptions. In this context, blockchain would not only serve as a protective IP infrastructure for the printing license management of design files, it would also make it possible to map the trading and sharing of production capacities. A Project Beta interviewee said, "When it comes to the sharing economy principle, I have certain quality requirements; I can search for a printer . . . and select a production asset that I use for the printing process."

Even though a secure blockchain environment could solve IP-related problems and issues with production capacity trading, shared factories will most likely remain a long-term vision. Large shared factories are complex and still require some trust among actors. While customers can define all kinds of specifications and feed them into the blockchain, the factory receiving the order still has some leeway. For example, the quality of 3D printed parts depends on the quality of individual machines. And for most parts, post-processing activities such as sanding, polishing, gluing, coloring, or smoothing are necessary, and the quality of performing these activities varies among suppliers. In contrast to outsourcing printing to local 3D printing service providers, leveraging the network effect of the shared factory paradigm would require a more open blockchain infrastructure. According to the experts we interviewed, open (public) blockchain platforms create new barriers, such as data privacy and the management of data reading and writing permissions. Shared factories will probably need more time before they become a serious and practical business model option for manufacturing firms.

Secure Design Marketplaces

Many of our experts mentioned that 3D printing platforms could transform into secure design marketplaces that function as a distribution channel for consumers and firms to sell their designs but also invite external designers into a firm's value creation process. While there are already 3D design marketplaces for decorative items or toys in private consumer settings (for example, online platforms like Pinshape, Threeding, and Shapeways), they have not yet come to industrial ecosystems. According to our interviewees, professional designers and firms often hesitate to use such platforms due to insufficient IP protection. Once they upload their designs, firms need to trust both the platform providers and the users to use the designs strictly as intended. For instance, firms typically have no control over how often their designs are printed, and whether they have been passed to third parties or resold. Blockchain addresses these concerns and helps to safeguard designers' IP with a protective infrastructure.

With such marketplaces, part designers (like OEMs) could be paid per print or offer subscription models similar to those predominantly used in the entertainment and media industry. One Project Beta interviewee described the monetization of IP: "The originator has the right to sell the IP in the future. . . . When entering the platform, he is now able to reach many buyers he was not able to before." Another Project Beta interviewee said, "I do not know whether these designer markets will be a business model [within the next few years]. But let me turn it around: . . . If there will be a business model like this, then only this way [based on blockchain]."

Given blockchain's origins in the financial services industry, the settlement of all monetary transactions could easily be mapped on the underlying blockchain infrastructure, without the need for trusted platform intermediaries. As a first use case, one external 3D printing expert we interviewed suggested the jewelry market is particularly attractive given the special characteristics of its products: "You are paying for the brand and for design and you are paying for high-value material. . . . so I could see a blockchain environment where international designers design jewelry whether it's watchstraps, bracelets, etc., and they make those designs available in a blockchain environment, where localized retailers could print these parts because they still require finishing and polishing and stone setting but all of that is done by local jewelers."

Most firms tend to choose inside-out innovation processes for innovations that do not fit their current business model and thus are not commercialized internally. Xerox and IBM have opened up their internal inventions to external firms, mainly through licensing, spin-offs, or disinvestments (Chesbrough and Rosenbloom 2002). By offering new distribution channels and the possibility to monetize unused designs, a blockchain-based marketplace could create similar new revenue streams for firms.

Conclusion

Researchers and experts praise 3D printing as a technology that drives business model innovation, but most firms that have adopted 3D printing have not yet altered the way they create, deliver, or capture value. Businesses have not leveraged interorganizational business models due to inherent threats within distributed 3D printing that pertain to IP management and data security. Blockchain technology seems to be a promising solution. Specifically, the immutable blockchain ledger can safeguard various types of part-related historic records, making key printing parameters, material specifications, or certifications non-repudiable. Smart contracts help to transfer sensitive data, such as printing licenses for sensitive design files, and to execute payments among numerous 3D printing stakeholders.

Based on these features, blockchain could be the appropriate infrastructure for interorganizational 3D printing networks. As such, blockchain could facilitate the emergence of three business models: local 3D printing, shared factories, and secure design marketplaces.

However, to leverage blockchain's potential in 3D printing, businesses must overcome many barriers, some of which do not pertain to blockchain's maturity. These barriers include the development of stakeholder governance concepts, corporate cultures that do not support sharing and ecosystem development, and data privacy-related regulatory conditions. On a technical level, the way of bridging physical printing parts and the digital blockchain ledger needs further attention. Despite these challenges, we believe that blockchain can become the underlying infrastructure of future 3D printing value chains, as it can address important IP and data security concerns and pave the way for numerous opportunities for business model innovation. Large players in aviation such as Honeywell, Air New Zealand, and Moog have begun to explore these opportunities. If more firms collaborate and also launch their own pilot projects to build internal blockchain capabilities, they would enhance understanding of how blockchain can help to improve the value proposition, creation, capture, and network in 3D printing ecosystems, exploit the potentials 3D printing offers, and thereby offer a viable source of competitive advantage in the future.

Acknowledgements
Chander Velu would like to acknowledge funding from the Engineering and Physical Sciences Research Council (EP/R024367/1 and EP/K039598/1).

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Text Box: What is Blockchain?

Blockchain technology is "a database architecture which enables the keeping and sharing of records in a distributed and decentralized way, while ensuring its integrity through the use of consensus-based validation protocols and cryptographic signatures" (Benos, Garratt, Gurrola-Perezet 2017, p. 1). All data inputs (transactions) are stored in blocks, which are chronologically timestamped and cryptographically linked through their unique hash values (unique fingerprints). Each block contains the previous block's hash value, making these elements a coherent chain (Babich and Hilary 2020). For every new data block, the blockchain protocol requires consensus across the network, guaranteed through consensus algorithms (for example, Proof-of-Work, Proof-of-Stake). Where there is consensus achievement, the validated block is added to the chain. Potential infringement attempts of already validated blocks would alter the block's unique hash value, and the hash values of all downstream blocks making manipulation easy to detect. Public-key cryptography-enabled digital signatures further ensure the authenticity of recorded transactions. Taken together, these mechanisms establish the blockchain's key features—immutability, non-repudiation, distribution, consensus validation, and smart contracts—which are crucial for the 3D printing ecosystem.

Table 1.—Overview of investigated projects and experts

Project	Expert ID	Expert Role in Project	Expert Position in Firm	Industry	Employees
Alpha (Germany)	A1	Co-founder	Managing Director	Software	250–500
	A2	Project member	Researcher	Academia	–
	A3	Co-founder	Project Leader	Semiconductors	30,000
	A4	Project member	Partner, Lawyer	IT Law firm	1,500
Beta (Germany)	B1	Co-founder	Senior Manager	Utility company	40,000
	B2	Project member	Corporate Strategy Manager	Financial services	50,000
Gamma (Italy)	G1	Founder	Founder and CEO	3D printing startup	< 20
External blockchain experts	BE1	–	Professor and Technical Advisor	Academia	–
	BE2	–	Researcher	Blockchain research center	–
	BE3	–	Researcher	Blockchain research center	–
	BE4	–	Researcher	Academia	–
External 3D printing experts	AE1	–	Vice President	3D printer manufacturer	1,000-5,000
	AE2	–	3D printing Advisor	3D printer manufacturer	10,000-15,000
	AE3	–	Founder and CEO	3D printing startup	< 10

Table 2.—Blockchain in 3D printing affects all business model elements

Business Model Opportunities	Value Proposition	Value Creation	Value Capture	Value Network
Local manufacturing	• Offer an improved value delivery (local, on-demand printing) • Offer less expensive products (cut	• Secure transfer of design files • Production outsourcing to local manufacturers, service providers, or customers	• Improved cost structures due to reduced transaction costs • Altered cost structures from fix costs to variable costs	• 3D printing service providers • Prosumers (higher customer centricity) • All stakeholders

	logistics costs)	• Full transparency about a printed part's lifecycle		sharing part related data
Shared factories	• Offer flexible production capacities • Offer an improved value delivery	• Secure transfer of design files • Secure and efficient blockchain-based payment processes • Counterfeit products become detectable	• Monetization of unused production capacity • Improved cost structure due to access to external capacities (decreasing fix costs) and maximization of production utilization	• Firms renting production capacities • Firms offering production capacities • 3D printing service providers
Secure design marketplaces	• Offer further 3D designs • Offer more customized products	• Secure transfer of design files • Increasing design variety und customization options	• Monetization of unused designs • Reduced development costs through external design procurement	• External designers • New customers

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