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Decentralised additive manufacturing for architecture: exploring the integration of distributed ledger technologies with 3D printing.

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Decentralised Additive Manufacturing for Architecture

Exploring the integration of distributed ledger technologies with 3D printing

Yorgos Berdos[1], Jiří Vele[2], Theodoros Dounas[3]
[1] University of Edinburgh, University of Dundee [2] Czech Technical University of Prague
[3]Robert Gordon University
[1] yorgos.berdos@ed.ac.uk [2] jiri.vele@cvut.cz [3]t.dounas@rgu.ac.uk

This paper investigates the potential integration of blockchain and distributed ledger technologies with Additive Manufacturing in the context of architectural design and fabrication. The study aims to identify knowledge gaps, explore the affinity between these technologies, and challenge the current architecture production paradigm. Through a comprehensive state-of-the-art review and analysis of academic papers and industrial case studies, we identified emerging themes and gaps in the literature. We also examined the misalignment of incentives among key participants of the proposed systems. Our findings highlighted the relevance of blockchain technology in additive manufacturing, but also revealed significant challenges and misalignments in incentives among stakeholders. We argue that further research and experimentation are necessary to fully understand the technical feasibility and impact of integrating these technologies in architectural design and fabrication.

Keywords: *Blockchain, Additive Manufacturing, 3D-printing, Integration, Distributed Ledger Technologies, Distributed Manufacturing.*

INTRODUCTION

The Fourth Industrial revolution professes to advance an automation in production that would be difficult to conceive without the existence of a multitude of automation technologies, such as the internet of things, distributed ledger technologies, and machine learning. Beyond the existence of the technology, it is the integration of the technology with production concepts and the economy that brings forth the advancement. This paper explores the possibility for integrating blockchain and distributed ledgers with additive manufacturing or three-dimensional printing in an effort to advance the envelope of improvements in the production of architectural design and fabrication.

DEFINITIONS

Blockchain (BC) is a public distributed digital ledger technology (DLT) that facilitates secure and transparent transactions between parties without intermediaries. It employs cryptographic techniques to maintain data integrity, providing an immutable and tamper-proof record of all transactions, due to the consensus algorithms used. Introduced with Bitcoin's whitepaper in 2009, blockchain has gained popularity in recent years due to its potential to revolutionise various industries by shifting trust and coordination at the level of the computer protocol. The second generation of BCs such as Ethereum (ethereum.org) has a set of features that allow them to execute classes of code, called smart contracts. The contract part does not have legal meaning per se, but communicates that the code excision is trustworthy and reliable, automatic and without intermediaries. Within smart contracts, one can build tokens and financial incentives and systematise token engineering, which can have an impact in the process of architectural design (Dounas et al 2022, Dounas et al 2021) as one can streamline collaboration processes, reduce costs, save time and minimise disputes. This further introduces the idea of decentralisation in the sense that processes execution and trust shift to the computation layer, allowing anyone to use the blockchain for productive purposes, i.e no central authorisation is needed.

In Additive manufacturing (AM) the three-dimensional object is created layer by layer. This method offers rapid prototyping and fast production of complex and unique parts with lower manufacturing costs, as the set-up of complicated manufacturing tooling is not required for the production. No need of moulds or forms and possibility to print near hollow objects reduces the amount of used material. Kubáč, L. and Kodym, O. (2017) state that AM has a potential to improve the supply chain by simplifying production processes, reducing material waste, increasing production flexibility and decentralising production. Schniederjans, D.G. (2017) compares injection moulding with current 3D-printer technology, which consumes 50–100 times more electrical energy to make the same item. Also, the production time is longer. In parallel Schniederjans, D.G. (2017) also pointed out the lack of proper legislation to protect manufacturers' intellectual property.

The integration of BC and DLTs with AM might offer a range of potential benefits, although further exploration and research are necessary to fully understand these possibilities. One area of interest is the potential for BC-based decentralised fabrication and distributed manufacturing to foster design collaboration and innovation. This approach could democratise access to complex manufacturing processes, potentially leading to a more sustainable and equitable design ecosystem. Non-fungible tokens (NFTs) on smart contracts might offer intriguing prospects for the creation, ownership, and secure trading of unique digital designs and artworks. As NFTs represent distinctive digital assets verified on a blockchain, they cannot be replicated. This aspect of NFTs could unlock new opportunities for artists and designers.

Within the context of architectural design and AM, BC technology might have the capacity to empower designers and local creators, strengthen supply chain resilience, and reduce transportation-related emissions through decentralised and distributed manufacturing processes. However, these potential advantages require further investigation to fully grasp their technical feasibility and impact.

AIMS & OBJECTIVES

The paper explores the affinity of the two industry 4.0 technologies in terms of integration and of disruptive change in the production of architectural design and fabrication. The scope is to identify the knowledge gaps that might exist around the integration of these two technologies, but also, more profoundly, to challenge the status quo of the current production paradigm of architectural design and fabrication.

METHODOLOGY

In this study, we aimed to explore the potential affinity between blockchain technology and 3D printing. Our methodology consisted of several steps:

1. State-of-the-Art Review: We began by conducting a comprehensive review of the current state of BC and AM technologies integration. Utilising a snowball approach, we analysed both academic papers and industrial case studies, originating from a number of different disciplines, to gain a broad understanding of the subject matter.
2. Identification of Emerging Themes: Through our review, we identified several common themes, including Intellectual Property (IP) protection,

Quality Assurance, Governance, Digital Marketplace, and Hardware solutions.
3. Cross-Referencing and Scoring: We cross-referenced all the literature and industry case studies with the emergent themes, scoring each case study based on their affinity with the identified topics. This scoring process helped us pinpoint areas of strength and gaps that require further research, Table 1.
4. Investigating Misalignment of Incentives: Upon identifying gaps in the literature, we observed a misalignment of incentives among the different participants in the system: designers, consumers, and makers. We delved into the reasons behind this misalignment by examining the potential gains and challenges for each participating party in the system.
5. Addressing Incentive Issues for Makers: Our investigation revealed that makers, who would host the distributed additive manufacturing process, faced more challenges and were less incentivised than designers and consumers to participate in the system. To address this issue, we developed a four-tier manufacturing workshop classification system aimed at making BC integration more appealing to AM fabricators while acknowledging the complexity of the endeavour, Table 2.

To determine a workshop's tier position, we used four criteria. Firstly, the Expertise Level: The first two tiers are designated for semi-professional workshops, while the top two tiers are reserved for professional workshops. Second, the Hardware Requirements: To advance to higher tiers, workshops must establish a connection between their 3D printer and the blockchain. Third, the Print Cases: Lower-tier workshops can participate by printing everyday objects, while higher-tier workshops have the capability to print high-end products and industrial parts. Fourth, the Trade-offs: The first tier requires no initial hardware investment to participate, but is limited to printing low-end products with reduced profitability. As workshops progress to higher tiers, they face increased initial hardware costs but gain the ability to print high-end design objects or industrial parts, potentially leading to greater profitability.

By employing these methods, we were able to reinforce our hypothesis about the relevance of blockchain technology with AM as well as identifying recurring themes in the relevant case studies, and highlight important gaps. As part of our ongoing efforts to address some of the gaps, we identified the key participants in the proposed ecosystem, and we proposed a tiered workshop classification system, Table 2, to better understand the incentives alignment issue among the key stakeholders involved in the integration of blockchain and 3D printing.

LITERATURE REVIEW

Kasten, J.E. (2020) provides a systematic review of the uses of blockchain for engineering and manufacturing. The themes identified concentrate on BC to protect data validity, to enhance inter-and cross organisation and project collaboration and communication, and blockchain to increase the efficiency of the manufacturing process. All three of these themes are present within the literature of integrating BC with AM.

Alkhader, W. *et al.* (2020) utilises Ethereum and the Interplanetary File System (IPFS) to enable reliable and authenticated traceability throughout the entire additive manufacturing process. They propose and also test system architecture which provides visibility of a product throughout their lifecycle, minimises human involvement in order to reduce lead times and offers secure traceability and certification of 3D printed products. Their Ethereum smart contract communicates and signs transactions between a customer, 3d printing workshop, digital product manager and a certification authority. All designs, print data collected during the printing by IoT and videos of the final product are stored on IPFS to prove authenticity. This system offers a reliable solution, but the question remains who will be the certification authority and how difficult it will be to upgrade commonly used desktop printers with proposed hardware.

In order to assure traceability and context of product origin, Holland, M. *et al.* (2017) propose the use of visible and invisible labelling systems. Such techniques include security tags, RFID, holograms, and security pigments. All these might be automatically added by the printer, without the possibility of counterfeiting it by a human. Combined with BC, a "Chain of Trust" can be developed in order to secure the authenticity of printing data and prevent unauthorised use.

BC-based platforms for 3D printing are developed by several entities. Klöckner, M. *et al.* (2020) interviewed experts and analysed publicly available data from such three consortia projects. Interviews highlighted three key issues, which current additive manufacturing faces. Those are unauthorised use of intellectual property, counterfeiting, and malicious data manipulation. Consorcia projects are using blockchain to protect and share data, such as printing licences, production process data, material provenance, test and simulation data, payment records, and certifications. Their goal is to develop new business models like local manufacturing, shared factories and secure design marketplaces.

Wang, Y. *et al.* (2022) tested an approach to ensure the safety of STL files by resisting tampering and leveraging the reliability and security of blockchain technology. The proposed solution involves using blockchain technology to secure 3D model data (STL files) by storing their "fingerprints" (hashes) on the blockchain. A hash function is used to extract these fingerprints, which have unique and fixed-length output for each model. The hash function ensures data integrity and can detect if the original data has been tampered with. To address the storage issue, the authors store only the cryptographic hashes of the 3d files on the BC, instead of the actual 3D models. The process involves the designer uploading their model, the system calculating the hash, and storing the fingerprint on the blockchain. When an operator downloads a model for printing, the authorised printer, which is a node in the blockchain, verifies the model's hash against a list stored on BC smart contracts. The printer only prints files whose hashes are on the SC secured list, ensuring the authenticity and security of the 3D models.

Kurpjuweit et al (2021) discuss the impact of blockchain on additive manufacturing as it relates to logistics and supply chains. They acknowledge that BC addresses important limitations of Additive manufacturing, and focus on blockchain playing the role of a secure peer to peer network of transactions, resulting in supply chain visibility. Additionally, they discuss how BC can assist in resolving two issues with AM. AM relies on the sharing of digital data assets, in sensitive generative processes. Iteratively developed, changed and optimised to manufacture the physical asset. BC could assist in the creation of decentralised networks of digital assets, that maintain and safeguard information integrity, ensure fabricability and data ownership, but potentially also go beyond that. Second BC can assist in the certification and integrity of the AM produced physical artefact, that can assist in information transparency throughout the lifecycle of the physical asset. The paper describes AM and BC led implications in the changes in the supply chain developed out of the two applications. Methodologically the paper only develops through expert interviews offering little space for operational testing of its assumptions. Some of the assumptions on the future impact of BC on AM supply chain are incredibly interesting, starting from the creation of decentralised AM manufacturing networks, and ranging from flexibility and agility in the supply chain, to shifting orders from one AM to another, resilience in production in AM networks as one could switch suppliers easily in the case of disruptions, increase agility in production with short lead times.

Berdos, Y. and Dounas, T. (2022) strategically analysed the outputs of architectural design studios in academic contexts to frame creative overlaps and shape relevant thematic clusters between BC and architectural production. Some of the emerging clusters included Modularity, Collaborative Fabrication, and Stigmergic Assembly, topics which have a high conceptual affinity with AM in the building scale.

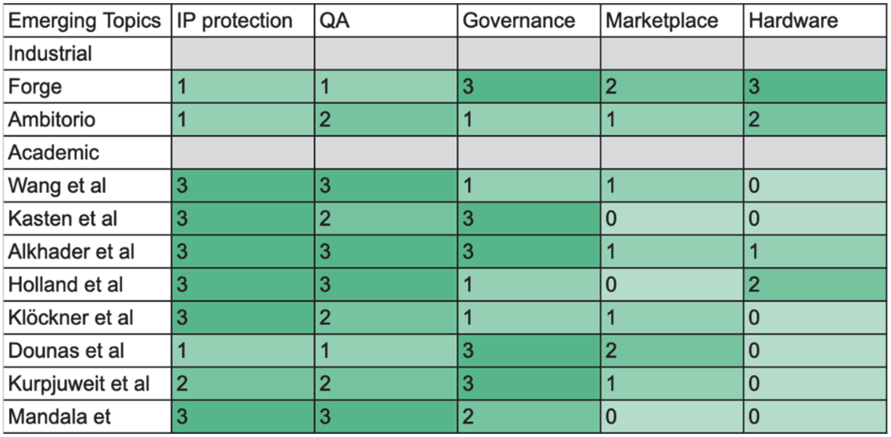
Mandolla, C. *et al.* (2019) describe the process of using BC as the bedrock of a digital twin for AM production processes in the aircraft industry. Within the paper the focus is on securing information end to end in the manufacturing process that heavily uses AM, ensuring quality and traceability, but also compliance with safety conditions, a neuralgic issue for the aircraft industry. Indeed, the paper presents a theoretical case study of using blockchain as the digital twin of the supply chain process. There are four phases presented within the supply chain presented: (1.) Scan and design (2.) Build and Monitor (3.) Test and Validate (4.) Deliver and Manage.

The scan and design part are interesting as it assumes that a major starting point of an AM process is the scanning of an already existing component. Scan verifiability is then an issue, with which BC can help via recording the calibration of the scan to ensure conformity to the original. The Build phase also mentions the distributed nature of AM as a process and the same issues mentioned by other authors where BC can help: auditability of the process, supply chain transparency of components, resilience of the production, the creation of a chain of custody for both digital assets and physical assets in a unified layer. The test and validate process follows similar logic, while the delivery and management deals with the somewhat unseen processes of mundane component delivery to its destination, payments etc. The paper presents a really simple example of signing and validating a G-Code for a model, by including the full .txt file into a block of a blockchain, a feat which is only sustainable in test BC as the authors admit, due to the size of the files.

INDUSTRY ATTEMPTS TO INTEGRATE BLOCKCHAIN WITH ADDITIVE MANUFACTURING

Forge was introduced in October 2018 as a solution that integrates BC and IPFS technology for decentralised content storage and transaction processing in the 3D printing industry. The platform suggested the use of an Ethereum-based ERC-20 token called FMX. Forge's product architecture consisted of several modules, a mobile app, and a range of purpose-built consumer-grade 3D printers. The platform aspired to operate as a decentralised application (DApp), using Ethereum for smart contract transactions and IPFS for storing 3D content and non-transactional data. Forge aimed to serve various user roles, including clients, vendors, designers, and consumers. It would offer a subscription-based model with fees, rewards, and payments in FMX tokens. The platform also enabled design challenges with bounties for successful designers and aimed at facilitating collaboration between different intellectual property owners. The different 3D printer designs were produced using open-source code and according to the team, were ready for production.

However, the project did not materialise as the approach seemed to be overly complex, due to the limitation of relying on purpose built 3d-printers. The requirement for specialized hardware introduces several challenges. First, it creates a barrier to entry for smaller businesses and individuals, as the additional costs and complexities of acquiring and maintaining such hardware may be prohibitive. Additionally, the need for specialized hardware may result in compatibility issues, making it difficult for various manufacturers and users to collaborate seamlessly, in an already established network of 3d-printers. Moreover, the development of specialized hardware may be time-consuming and resource-intensive, which could slow down the widespread adoption of blockchain-enabled 3D printing. Lastly, the reliance on specific hardware components could make the system more vulnerable to disruptions in supply chains or single



Emerging Topics	IP protection	QA	Governance	Marketplace	Hardware
Industrial					
Forge	1	1	3	2	3
Ambitorio	1	2	1	1	2
Academic					
Wang et al	3	3	1	1	0
Kasten et al	3	2	3	0	0
Alkhader et al	3	3	3	1	1
Holland et al	3	3	1	0	2
Klöckner et al	3	2	1	1	0
Dounas et al	1	1	3	2	0
Kurpjuweit et al	2	2	3	1	0
Mandala et	3	3	2	0	0

Table 1
state of the art industrial and academic projects, with scoring based on the emerging topics

points of failure, potentially undermining the benefits of a decentralised and secure manufacturing ecosystem.

The challenges in realising the vision of distributed manufacturing and how blockchain technology can help address them were discussed in an article (2022) on additive manufacturing media by Stefanie Hendrixson. The article outlines the risks associated with sharing 3D printable files, such as file tampering, unauthorised printing, and intellectual property theft. To establish trust and address these issues, CoreLedger, a company providing blockchain solutions, partnered with Ambitorio and worked on an Interreg-funded initiative. They developed a blockchain-based solution with three main objectives: securing 3D printable files via file hashing, protecting data access through tokenised access rights, and accounting for printing runs by requiring tokens for each print. Fabru integrated the blockchain system with its Plastjet 3C-855 fused filament fabrication (FFF) 3D printer by way of a Beelink mini-PC. The company claims to have successfully used the solution to send printable files to the machine and control batch sizes of those parts. However, existing 3D printing equipment will need to be retrofitted to utilise the blockchain solution. The article also introduces the idea of treating 3D printable objects like tradeable tokens, and trading unused printing capacity or machine utilisation in the form of tokens.

Table 1 contains the scoring of each case study based on their affinity with the emergent topics.

CONSTRAINTS AND KNOWLEDGE GAPS

The majority of papers mentions Internet of things and camera recording for validation of the 3d output, or even pushing for use of only one type of a printer for maintaining manufacturing standards. This requires great initial investment on the side of the manufacturing and excludes all small entities which will not allow for the development of a network effect that could reduce production costs and prices. In addition, Blockchain protection in the additive manufacturing industry is mentioned only on the side of Intellectual Property (IP) protection of the output of the designer or the customer, and in that only in abstract or concept phases without in depth technical work. The question that remains thus is on how will the additive manufacturing facility be protected from dishonest customers through the mechanisms of the BC, and could one develop trust systems that protect all three, i.e the designer, the customer and the fabricator. This is lateral to the question that most papers understand BC as a cyber-security technology without harnessing its network and economic level effects in changing the AM production.

The constraints we have found in our analysis of the existing literature point towards friction and technical constraints in integrating BC to AM. From the analysis of the emerging topics, it becomes interesting to note that there are few sources that explore the integration of BC with AM on a hardware level. Those that do on the industry side, have either failed or have not managed to engage the markets, mainly because their focus was on selling BC enabled AM. This means that either the integration needs to happen on another layer, for example the software or economic layer, or the hardware integration needs to be industry wide, i.e to have a 3d printer enabled with a BC node from almost all manufacturers. This points to the second constraint that we uncovered, which is the geometric scale of the AM application, as this can affect what strategy one takes with printing (in components or assemblable parts) if the object to be produced is bigger than the printer, or with specialised custom robotic hardware. In that a BC integrated process can be used to validate the design with the fabricated part and its assembly, or validate the output of the highly customisable robotic printer. Still, from the perspective of resilience, a BC to AM integration makes sense when one has a pool of printers, a pool of applications and a pool of users/customers, i.e when one has a marketplace that acts as a decentralised production and coordination pool. In the following paragraphs we explore the incentives and structure of such a pool speculatively.

DISCUSSION: INCENTIVES ALIGNMENT BETWEEN DESIGNERS, CUSTOMERS AND FABRICATORS

Our comprehensive literature review on the integration of blockchain with 3D printing technologies in various domains, revealed three primary actors with the system; the customer, the designer, and the maker. The customer refers to the non-industry expert that is willing to invest in a locally fabricated design piece, the designer refers to the original author of the digital artefact, and the maker to the fabrication facility able to materialise the digital design using 3d printing. The blockchain technology emerges as a communication interface between the three, mediating the processes and facilitating intellectual property (IP) protection, as well as traceability of objects among these stakeholders.

The participating customers in the system can benefit from a number of factors. Firstly, they can take advantage of blockchain's transparent and verifiable record keeping apparatus, to gain access to information regarding the origins of the printed object, its production history, evolution, and environmental footprint. This traceability allows for greater quality assurance as part of the system, as the produced objects could be verified using 3d-scanning technologies, ensuring the consistency of the outputs regardless of the geographical location of the maker. The customers can also have the opportunity to invest in the design of objects that are yet to materialise, harnessing the potential for trust shifting to the computer protocol but also for the potential high value digital scarcity embedded in blockchain based systems. Additionally, the potential for adaptation, customisation, and personalisation of the designed artefact that someone wants to acquire is of high value potentially to the customer, while still recognising the authorship of the original designer and compensating them fairly. Finally, the integration of blockchain technologies in a 3d printing ecosystem can streamline the purchasing and reselling of designs or digital fabrication instructions in the form of code, making it easier for customers to access a variety of unique, original, high quality, potentially customisable, 3d-printable objects.

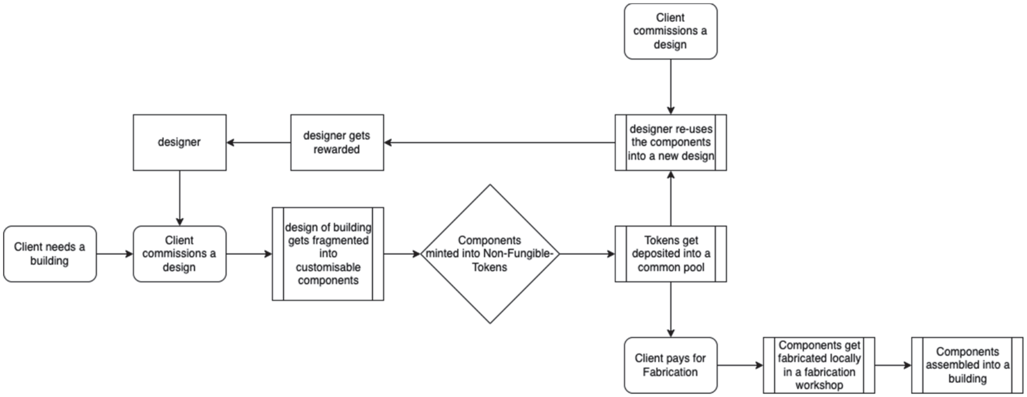


Figure 1
Tokenisation and financial incentives used in a common pool of designs and design components

The structure of particular token smart contracts can be such that the original designer is compensated every time there is a re-selling of an artefact.

Apart from the customers, the participating designers can benefit from the potential of various customers willing to invest in their designs (Figure 1).

The designers can also maintain royalties for any further execution of their design or future sale, utilising smart contracts. This ensures fair compensation for designers and encourages them to continue producing and publishing innovative work. The designers can also be encouraged by the system, to attempt to address design problems collectively, knowing that a wider adoption of their design solution will be translated into greater gains for them. They can also benefit from the increased visibility that a blockchain based open marketplace can offer, enabling designers to gain exposure to wide customer bases. This exposure will come without risking IP infringement, since blockchain could offer a secure and tamper proof way of preventing unauthorised replication of their work. This extends creates the outline of a common pool of design resources where one could potentially apply Ostrom Principles enabled through blockchain (Ostrom 2005, Hunhenvicz 2022).

When focusing on the perspective of the makers, it became apparent that the current systems that are being explored offer limited incentives for fabricators and workshops to participate. Existing platform models, such as Cubee Inc. (2022), already enable makers to become visible on the network and engage with distributed fabrication, without the need to engage with complex technological blockchain based solutions. Moreover, the significant expenses associated with the necessary IoT hardware, the connection of the printers to the blockchain, and the need to standardise or calibrate the printers with others participating on the network to be able to achieve consistent outputs. This substantial investment in terms of time, effort, and money comes with questionable benefits from the perspective of the workshop so it can be often considered as the reason why these projects are struggling to gain traction. Some of the positive incentives for participation in the system from the customer or designer perspectives are not aligned with the makers interests, as the IP protection, traceability, customisation, and participation to the marketplace would need significant investments and upgrades from the makers side, unlike the designers of the customers.

On the other hand, it is important to point out that print quality can vary significantly from maker to maker, and some workshops may produce lower quality prints than others. Factors influencing the quality of the final outputs include the nature of the hardware-printer, the consistency of the material, environmental factors, and fabrication skills of the manufacturer. One potential solution to start addressing this issue and enhance the appeal of blockchain – 3d printing integration for the makers is to categorise the workshop facilities into four distinct tiers, enabling the customers to identify the most suitable tier for their printing needs. As shown on Table 2, Tiers 1 and 2 would represent semi-professional makers requiring little to no initial investment to participate. These workshops would offer lower manufacturing prices but would not guarantee the same level of quality or consistency as higher tier workshops. Tiers 3 and 4 would include professional workshops, with a proven track record and committed to delivering consistent high-quality prints, IP protection, and traceability. While manufacturing prices for these tiers will be higher, customers would be able to select based on their requirements, quality expectations and the technical specifications set by the initial designer.

Table 2
Fabricators tier system description

Tier	Description	Printing use cases
1	Access to the decentralized marketplace, Blockchain as a payment solution and a reputation system	Household tools, toys
2	Tier 1 requirements, Printer connected to the blockchain granting IP protection	Design objects, jewelry
3	Tier 2 requirements, IoT sensors tracking process of printing	Design and fashion brands
4	Tier 3 requirements, Printers are watermarking objects for traceability	Industry parts

CONCLUSIONS

We believe that our paper has clearly shown that there is incentives misalignment between the designers, the customers and the fabricators in a BC enabled AM marketplace scenario, as the cost for the fabricator for entering such a marketplace is very high. An additional tension is the clash between digital scarcity promoted by many Non-Fungible Token projects and the idea that a common pool of fabrication facilities can enable a more equitable distribution of goods. We can speculate however that there are pockets of alignment where one can explore incentives, trust and production alignment. This will have to take initially the form of a blockchain enabled collective additive manufacturing experiment, which is not easy to document here. We are however in the early stages of developing such a system that could validate the assumptions and logical analysis presented in this paper.

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