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Towards a Decentralized Physical Infrastructure for Additive Manufacturing in Architecture

A proof of concept for a tamper proof, secure connection between designs, blockchains and 3d printers

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We introduce a promising proof of concept: a blockchain to additive manufacturing pilot prototype. In this paper we focus on developing the functional cyberphysical prototype of the smart contracts running on a blockchain, orchestrating the workflow of additive manufacturing in architecture. We have used design science research and rapid prototyping as methods to create our cyberphysical system. Our prototype allows for the discretisation of a design in components, which are then placed for bidding for production. The components are indexed, with a Non-Fungible Token is produced for each component, recorded on the smart contracts of our platform. The original designers are recorded and then rewarded if the component is ever re-used. A set of additive manufacturing shops then cost and bid for the production of the components, recording their bid on-chain. Component fabrication quality is then validated against the tamper-proof blockchain storage system. Our pilot project establishes viability and a direct link between a blockchain network and 3D printers, facilitated by microcontrollers interfaces acting as blockchain "Oracles". The significance of this paper lies in its potential to reshape the architectural manufacturing and fabrication landscape. By integrating blockchain with 3D printing, we address critical issues such as efficiency, in challenging locations with labour shortages or logistical constraints.

Keywords: *Blockchain, Additive Manufacturing, Common Pool resources, Decentralised Manufacturing*

INTRODUCTION

Efficient supply chains from design to fabrication to construction remain an open question in the architecture engineering construction ecosystem. Due to the fragmentation of the AEC ecosystem, it is difficult to find the benefits of supply chain integration, since every project in construction requires the mobilization of a divergent, variable set of project participants, which then dissolves, along with the knowledge they have. On a second level, design for particular fabrication technologies, for example laser cutting or 3d printing, requires knowledge and expertise that is finetuned to that particular technology. While the promise of additive manufacturing and 3d printing has been high the technology has not been adopted in large parts of the construction industry, as it still has application constraints at the scale of the architectural object:

scale, material handling and quality, lack of proper tooling. In some cases, there have been production advances, where one oversized 3d printer is used to produce the main structure of a building as mentioned by Puzatova et al (2022). In others, where the size of the printer is not larger than the edifice, 3d printing is used to produce simple components that are then assembled in a kit of parts. This latter approach is the focus of our study. Compartmentalization into parts makes the system more complex and introduces additional complexity due to the necessary assembly. However, it also provides the possibility for a decentralized manufacturing solution, resulting in a more robust and reliable system with multiple levels of backups. Decentralized manufacturing, tracked with blockchain technology, addresses these constraints by enhancing data security, ensuring quality control through tamper-proof records, and facilitating decentralized decision-making processes.

OBJECTIVES, MOTIVATION AND DEFINITIONS

The objective of this paper is to showcase the implementation of a blockchain-enabled process of 3d printing (under scale) a component of an architectural design. To achieve the objective we ask the question on what are the minimum viable parameters under which three parties, the designer, the manufacturer and the customer can securely exchange data, introduce anti-tampering and quality control measures and execute payments upon the successful design and fabrication of a component. In a related work we have outlined how our decentralised platform develops the fragmentation and discretisation of the components so that they can be produced using additive manufacturing from a dispersed set of fabricators. Essentially we are creating a proof of concept where designers, fabricators and customers participate in a common pool coordination scheme with aligned incentives, with blockchain smart contracts taking care of all data curation and payments and additive manufacturing providing the physical output.

Blockchain, Smart contracts and Tokens, and Decentralised Storage

A blockchain is a distributed digital network where all nodes via an algorithmic consensus method store the same ledger of transactions. As a decentralised Ledger technology, a Blockchain can run smart contracts, classes of software that execute automatically and autonomously. On Smart Contracts, one can create Fungible and non-Fungible tokens, i.e unique or repeatable abstract representations that allow for elaborate economic and design behaviours to emerge. Decentralised storage is a set of internet nodes that hold content identifiable not by address but by a content identifier. Examples used in this paper include the InterPlanetary Filesystem IPFS. [Dounas et al 2020, 2021, 2022. Berdos 2023]

Additive Manufacturing

Additive Manufacturing, colloquially referred to as 3D printing, is a fabrication process in which a three-dimensional object is constructed through the incremental deposition of material, layer by layer. This methodology involves the initial creation of a digital model, which is subsequently partitioned into cross-sectional slices. These slices are then translated into a set of movement instructions, typically in the form of G-code, which guide the operation of the 3D printer. The printer executes these instructions, methodically depositing material in a stratified manner, thereby gradually forming the desired object. In contrast to traditional moulding techniques, objects produced through additive manufacturing exhibit a comparatively rougher surface finish. However, this process offers several notable advantages, including the facilitation of rapid prototyping, cost-effective production, and the ability to customize designs with relative ease.

Common Pool Resources Problem

In economics, a CPR is a system of natural or human made resources that is subject to depletion from overconsumption, i.e the tragedy of the commons which can only be prevented by cooperation and consensus.

BACKGROUND

Various researchers have conducted work earlier in the affinity of blockchain and additive manufacturing. The issues emerging out of these earlier work revolve around copyright and intellectual property protection, trust in a fabrication network and in between stakeholders, incentives alignment between stakeholders participating in the system, safety and quality in distributed production but also discretisation of a design so that it is easy to facilitate distributed manufacturing.

Ghimire et al (2022) develop the recent trends and future possibilities on combining BC with Additive manufacturing. Within this envelope they identify secure storage of data and IP, traceability and authentication with the share quality key performance indicators while smart contracts can ensure sharing of files with no loss or risk of manipulation leading in complete process automation for 3d fabrication. Kasten (2020) develops a systematic review of the common issues of blockchain with manufacturing, concentrating on the issue of data validity, enhancing intra and cross organisation collaboration and optimizing efficiency of the manufacturing process.

Intellectual Property

Esmaeilian et al (2019) describe a theoretical BC platform for protecting intellectual property that uses blockchain and smart contracts, where digital files are stored and retrieved on-chain, along with the usage and IP licensing rights and appropriate rewards and incentives. They also mention the benefits of decentralized fabrication, where components are produced close to the site they will be used in. Holland et al (2017) describe the product and legal aspects of introducing a blockchain enabled additive manufacturing process. They identify the designer as vulnerable to IP theft and the need for enforcing IP rights, connect fabrication with trust, via BC enabled printers, and describe the benefits for this customer on protection against IP poisoning or design manipulation, but also confidence in the trustless process of the blockchain and advantages of guarantees that can be enclosed on chain.

Digital twins

Mandolla et al (2019) explain how a blockchain enabled Digital Twin platform for additive manufacturing in the aircraft industry can be build orchestrating all four phases of an additive manufacturing process, namely the scan and design, Build and monitor, test and validate and deliver and manage. As such a similar platform could be envisioned for the Architecture-Engineering-Construction industry.

Security and Quality

Shi et al (2021) describe the use of a blockchain for enabling the cybersecurity of the raw G-Code 3d printing data. They do so by using asymmetric key cryptography, encoding the g-code, storing it on IPFS and creating a unique CID, and then retrieving and decrypting the G-Code for printing.

Traceability and Decentralised Manufacturing

Alkhader et al develop functional loops between manufacturer and customer, along with the required pseudocode loops so that they can create fully traceable on the blockchain additive manufacturing parts. Again, the designer is implied here, or is engulfed within the role of the manufacturer, a condition that is separate in Architecture, along with the requirement for having an orchestration of parts rather than a single part. Monroy et al develop a set of concepts on decentralised manufacturing describing in the process the difference between a single manufacturing platform, a consortium of SMEs coming together into a single market for Additive manufacturing, but also the optimisation of idling resources between micro-factories or larger factories that can be funnelled towards larger manufacturing projects. Within their system architecture they identify a smart contract logic layer, a data storage and compute layer, a market and control layer. They uniquely identify the market optimisation problem, where the market needs to be regulated, that meets the physical constraints of the AM process, maintains acceptable pricing mechanisms for buyers, i.e is cheap enough for the majority of market participants, but also ensures a profit for manufacturers, a vicious incentive alignment. Product pricing however depends on the availability of manufacturing resources which in turn is dependant on the information on the decentralised market. Additionally, they describe the optimisation required for placing the fabrication facilities in optimal locations.

Circular Economy and Industrial Symbiosis

Ferreira et al (2023) describe industrial symbiotic ecosystems with the potential of using blockchain technology for the stigmergic collaboration between network partners. This can orchestrate a circular economy of additive manufacturing, where the supply chain of used materisl contributes to upcycling processes. Within their case study they identify value and monetary flows between stakeholders as the critical processes of the ecosystem.

METHODS

In earlier work we have described the process with which a design can be analysed into discrete components which can then be 3d printed. These components can be registered unto a smart contract and retrieved for 3d printing, along with their performance data, hence the manufacturer and the customer can have validate whether the produced component is of the required quality. In this current paper we present the cyber-physical prototype, which consists of a smart contract deployed on an Ethereum test network, a Raspberry Pi 3 b+ 4Gb board running MainSail Linux and Klipper, which is in turn connected to a generic 3d printer. The Mainsail linux has been modified by adding an IPFS node and the web3.py library on its python installation. along with a set of web3 python scripts so that the board can communicate bi-directionally with the smart contract on the test blockchain (Figure 1).

GCODE, SMART CONTRACT TOKEN AND IPFS

To validate our process we use an earlier case study of the Prvok building (Novakova et al 2021), which was was designed with 3DCP technology in mind and wall segments were defined as most suitable for 3D printing. The layout of the printed parts was designed to meet the reach capabilities of the printer - an ABB IRB 6700 industrial robot,

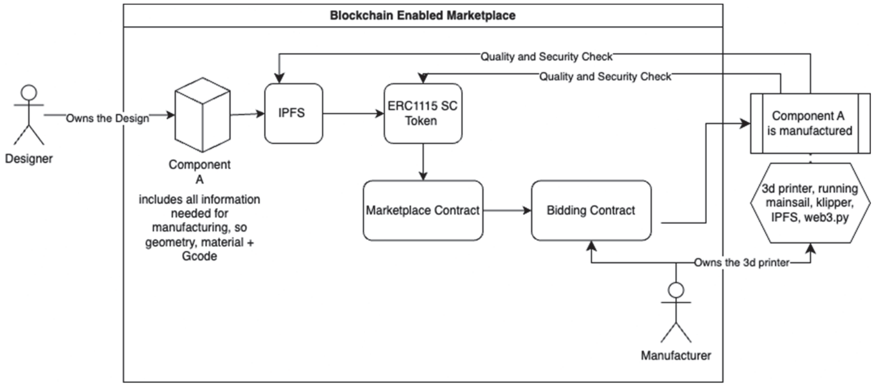

Figure 1: Printing a 3d component with the use of a smart contract and IPFS

with the added constraint that however the robot could not reach a height of 3.3 meters. We have adapted this to scale 1:20 so that it is suitable for testing purposes in a Voron 3d Printer without the capital expenditure of a full building, adapting also the layer height at 3mm and the width at 2.5mm. The printable parts of the building were analysed into discrete parts, which we then uploaded into IPFS, so that they receive a unique Content Identifier (CID)(Figure 2)

Interplanetary Filesystem

Within IPFS the component we are testing with has acquired the following CID

IPFS CID 1: QmP2v1xs7djKLAYGdQ4exUtBKQoUgX1v58zVStxvpW9xBg

While we use an ERC1155 smart contract to record and mint the CID as a Non-Fungible token so that we can secure the file, trace production and validate the quality of the print. The contract is deployed on the sepolia test network, with contract address 0x0d383BaA00ee927449a61a11464e88bd02f53A9a owned by the account 0xC3E782Db90bA08f25b44F47C7669c4Cc13A74327

```
function setURI(string memory newuri) public onlyOwner {
        _setURI(newuri);
    }

function mint(address account, uint256 id, uint256 amount, bytes memory data)
        public
        onlyOwner {
        _mint(account, id, amount, data);
    }
```

Retrieving then the component unto the printer takes place through IPFS unto the raspberry Pi that controls the printer with the following command

IPFS cat /ipfs/
QmP2v1xs7djKLAYGdQ4exUtBKQoUgX1v58zVStxvpW9xBg > ~/printer_data/gcodes/Prvok3.gcode

Which downloads unto the 3d printer the smart -contract recorded Gcode. With this process we are able to secure custody of the data between the designer of the building and the fabricator, trace who has printed the component and part, allowing for a distributed, decentralised production of the building components in an automated manner (figure 3).

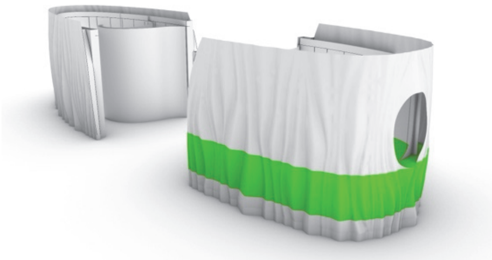

Figure 2
Discretisation of the Prvok walls into scaled components for use in testing

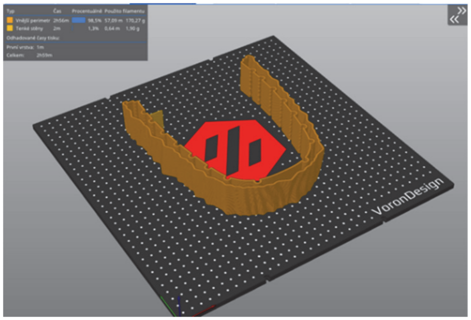

Figure 3
scaled 3d printing of the Prvok component after retrieval from IPFS/smart contract

Before printing a final control and check between the smart contract recorded CID and the content on the printer confirms the validity of the data. With the same process we can also distribute instructions for printing in terms of printer set up, for example temperatures, speed, material viscosity and density.

DISCUSSION AND CONSIDERATIONS

A critical issue for this research is the orchestration of a decentralized fabrication ecosystem that efficiently facilitates the coordination among designers, manufacturers, and customers. This ecosystem must enable secure data exchange, enforce quality control measures, and manage transactions for the design and fabrication of architectural components. The complexity of this coordination is magnified by the need to maintain a common pool of resources that must be managed and ensure sustained collaboration. For this process to function successfully, a harmonious common pool coordination mechanism that aligns the incentives of all stakeholders involved in the additive manufacturing process is needed. This mechanism must ensure that the designers, who contribute their intellectual property, the manufacturers, who bid and produce the components, and the customers, who require high-quality architectural elements, operate within a framework that is both transparent and secure. Blockchain technologies introduce a solution to this challenge by providing a decentralized platform that facilitates trust, traceability, and transparency among parties without the need for a centralized authority. One innovative aspect of solving the common pool coordination problem is the concept of investing in the designer or the design itself. By treating architectural designs not just as static intellectual property but as assets within a blockchain ecosystem, we can create a model where designs are tokenized. Each component of a design can be associated with a Non-Fungible Token (NFT), representing ownership, copyright, or usage rights. This not only ensures the protection of the designer's intellectual property but also opens up new avenues for investment in architectural designs.

Designers are rewarded through this system not just for the initial use of their designs but also for any subsequent re-use, incentivizing the creation of designs that are both innovative and adaptable. Manufacturers and customers can invest in these designs by purchasing tokens, thereby directly supporting the creation of new architectural components and solutions. This model promotes a symbiotic relationship between all stakeholders, fostering a collaborative environment that encourages innovation and flexibility. The potential to invest directly in designers or their designs represents a significant paradigm shift within the architectural landscape. This approach, facilitated by blockchain technology, opens new avenues for equity, participation, and the valuation of architectural work, starkly contrasting with traditional project methods.

Traditionally, architectural design has been constrained by the economics of commissioning and the physical limits of construction. Projects are often funded by clients who commission architects to bring their visions to life, with financial and creative control largely resting in the hands of a few stakeholders. This model can limit innovation and restrict participation to those with substantial resources. Furthermore, the valuation of architectural designs is often tied to the completed project's physical attributes, overlooking the intellectual and creative contributions of the designers. Investing directly in designers or their designs introduces a democratization of architectural creation and funding. By tokenizing architectural designs and components, blockchain technology enables these tokens to represent not just ownership but also investment in the creative process. This means that anyone can become a stakeholder in a design project, breaking down barriers to entry and diversifying the pool of contributors. This democratization could lead to a more equitable distribution of resources and opportunities within the architectural field, empowering emerging designers and underrepresented voices.

The implications for design innovation are profound. With a broader base of stakeholders, architectural projects can benefit from a wider range of inputs and ideas, fostering innovation and experimentation. Designers are incentivized to explore novel concepts and sustainable practices, knowing there is a platform that supports and values innovation. This could lead to a more vibrant and diverse architectural landscape, reflecting a wider array of cultural, environmental, and social considerations.

Participation becomes more meaningful in this new model. Stakeholders, with a direct investment in the success of a design, are more likely to engage with the project beyond financial contributions. This could manifest in community-driven design decisions, feedback loops between designers and investors, and a more collaborative approach to architectural creation. The result is architecture that is more responsive to the needs and desires of its community, fostering a sense of ownership and connection among all involved. Comparatively, this approach stands in stark contrast to traditional architectural practices, where financial and creative inputs are often limited to a select few, and community engagement can be an afterthought. By enabling direct investment in designers and their designs, blockchain technology can catalyze a shift towards more inclusive, innovative, and participatory architectural practices. This model not only elevates the role of the designer in the creative economy but also can enrich the architectural landscape with a diversity of voices and visions, making it more reflective of the collective aspirations of society.

CONCLUSIONS AND CHALLENGES

The venture into a blockchain-enabled additive manufacturing ecosystem in architecture introduces a dynamic solution to the intricate problem of coordinating common pool resources among designers, manufacturers, and clients. However, this approach brings forth several challenges and considerations that necessitate careful deliberation and strategic solutions.

Firstly, scalability emerges as a pivotal concern. As the ecosystem expands, incorporating an ever-growing array of designs, components, and participants, the underlying blockchain platform must adeptly manage an escalating volume of transactions. The challenge lies not only in maintaining the integrity and security of these transactions but also in ensuring that the system remains efficient and responsive. The architecture of the blockchain solution must be robust enough to support this expansion without succumbing to bottlenecks that could impede functionality or user experience.

Interoperability stands out as another critical challenge. The seamless flow of information between the digital realm of blockchain and the physical domain of additive manufacturing is essential. This includes the accurate representation of physical components as digital twins on the blockchain, ensuring that each digital counterpart reflects its physical manifestation with utmost precision. Achieving this level of synchronization requires a well-orchestrated integration of software and hardware, alongside protocols that facilitate communication between disparate systems and technologies. The goal is to create an ecosystem where digital and physical assets move in lockstep, governed by smart contracts that execute flawlessly in response to real-world triggers.

The issue of standardization also demands attention. For a decentralized ecosystem to function harmoniously, common standards for the tokenization of architectural designs and components are imperative. These standards must address the categorization, representation, and exchange of tokens within the ecosystem, ensuring that all participants speak a common language and adhere to agreed-upon protocols. This standardization extends to the quality control of manufactured components, the authentication of designs, and the execution of smart contracts.

Establishing these standards is a prerequisite for interoperability and for the prevention of ecosystem fragmentation.

Lastly, navigating the regulatory landscape presents a complex challenge. The legal implications of tokenizing intellectual property, executing smart contracts, and managing digital assets within a blockchain framework are vast and varied. Regulatory compliance must be meticulously considered to protect the rights of all stakeholders, including designers, manufacturers, and end-users. This includes the protection of intellectual property, the enforcement of contractual obligations, and the handling of disputes. The evolving nature of blockchain technology and its applications in architecture and manufacturing means that regulatory frameworks may need to adapt, requiring ongoing dialogue between innovators, legal experts, and policymakers.

While the integration of blockchain technology with additive manufacturing offers a promising path towards decentralized, collaborative architectural design and production, addressing these challenges is critical. Scalability, interoperability, standardization, and regulatory compliance are important factors for architecture to benefit from the full potential of blockchain and additive manufacturing technologies.

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