A Theoretical Framework for the Standardisation and Industrialisation of 3D Concrete Printing through Decentralised Science

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The industrialisation of 3D Concrete Printing represents a potential paradigm shift for the construction industry. Existing building codes, standards, and regulations at the local and regional scale are tailored to traditional construction methods and concrete casting: a regulatory framework specifically designed for the unique aspects of 3DCP is missing, constituting the principal barrier to the diffusion of this technology. This paper proposes a theoretical regulatory framework for 3DCP industrial application by theorising a robust, safe and reliable infrastructure for collecting, validating and distributing design and production data, using Decentralised Ledger Technologies as infrastructure for creating and maintaining the framework. Knowledge transfer methodologies are analysed and, together with ontology engineering, validate the proposed methodology. The decentralised system focuses on standardisation and regulation to guarantee accessibility and usability for stakeholders, as well as scalability and adaptability to local and regional regulatory requirements and standards.

Keywords: *3D Concrete Printing, Decentralised Ledger Technologies, Regulatory Framework, Knowledge Transfer, Ontology Engineering.*

INTRODUCTION

The contemporary performance-based approach to architectural design acknowledges the potential of 3D Concrete Printing (3DCP) in design flexibility, materials efficiency, sustainability, and structural optimisation and performance. The discretised layered deposition model allows for potential material quantity and quality adjustment within the 3D-Printed Concrete (3DPC) construct, setting an unprecedented advantage compared to traditional casted concrete. However, the possibility of creating optimised shapes depends on the material's composition and rheology (Marchon et al, 2018, pp. 96–110; Pessoa et al, 2021, p. 110794), which, in turn, determines the mixture's buildability and pumpability (Zhang et al, 2018, pp. 98–106) and the possibility of having good intra-layer and interlayer adhesion, ultimately affecting 3DPC mechanical and structural performance.

The need for codes and regulations for industrial applications of 3DCP has been pointed out in recent years (Diks, 2019; El-Sayegh, Romdhane and Manjikian, 2020, p. 34). However, the feasibility of such industrial applications remains controversial among scholars, with opposing views (Ning et al, 2021).

While production tools are already regulated in their industrial uses (*ISO/ASTM 52939*, 2023), and the first attempts to standardise materials and testing are proposed (Adamtsevich, Pustovgar and Adamtsevich, 2021, pp. 141–148; Ley-Hernández and Feys, 2020, pp. 228–236), no common and validated standards have been identified, and 3DCP is still restricted to small ornamental applications. Existing regulatory frameworks, in fact, are tailored to conventional construction, and therefore, they only target cast concrete applications. This constitutes a barrier to 3DCP adoption in the industry.

The same absence of standards and regulations undermines the universality of ongoing research on 3DCP, which is fragmented and produces potentially self-contained results, considering that there is no clear consensus, not even for the mechanical performance of 3DPC.

Establishing a regulatory framework for industrial applications of 3DCP is essential and requires addressing challenges related to material and structural strength, 3D printing technologies, design standards and guidelines, construction and maintenance (Ambily, Kaliyavaradhan and Rajendran, 2023, pp. 300–328).

RESEARCH BACKGROUND

This section draws from adjacent research in digital manufacturing, intellectual property law, and blockchain-based certification to outline a foundation for linking Decentralised Ledger Technologies (DLTs) with 3DCP.

The expansion of industrial 3D printing introduces unresolved copyright, regulatory compliance, and standardisation challenges, particularly as production shifts toward decentralised and industrial scales. Key issues include protecting digital assets and enforcing quality and safety standards across distributed networks. While advancing, 3D Concrete Printing (3DCP) remains hindered by the absence of unified technical standards and regulatory frameworks essential for industry-wide adoption.

Adamtsevich provides a comprehensive overview of how Russia is addressing the need for standardised test methods and material specifications for 3D concrete printing (Adamtsevich, Pustovgar and Adamtsevich, 2021, pp. 141–148). In a comprehensive overview, the paper discusses the critical challenges posed by the anisotropy of printed concrete layers, the interplay of adhesion between successive layers, and the unique rheological requirements of printable concretes. To overcome these challenges, the authors present the recently introduced Russian standards that regulate the properties and testing procedures for materials intended for 3DCP applications.

Romano introduces a novel framework integrating blockchain with 3D printing to address aeronautical part production and certification inefficiencies (Romano et al, 2024). By leveraging blockchain for the immutable storage of manufacturing and certification records, the study proposes a system where 3D-printed aircraft cabin parts can be locally produced and certified through blockchain-registered digital records, ensuring compliance with European Union Aviation Safety Agency (EASA) standards.

The work by Abe addresses a critical challenge in the context of personal digital fabrication, ensuring the traceability and accountability of 3D-printed products (Abe et al, 2022, pp.1-3). The authors introduce "Fabchain," a blockchain-based system that manages and records 3D print job histories over a decentralised ledger, specifically utilising Ethereum. The solution leverages blockchain's immutability and distributed nature to create tamper-resistant and sustainably accessible fabrication records, essential for assigning liability in product failure cases. Fabchain operates as an auditable communication channel between print clients and servers, securely logging print requests and their outcomes onto the blockchain. The authors implemented a prototype of Fabchain and demonstrated its capability to manage print job

communications in under one minute on the Ethereum test network, validating its practicality for real-world 3D printing workflows. Additionally, the study presents a comparative security analysis between Fabchain and centralised history-publishing services, highlighting the advantages of decentralisation regarding the integrity and availability of fabrication records.

De Filippi analyses how the blockchain, as a decentralised and trustless infrastructure, accelerates the codification of legal norms into programmable logic. The study tracks this transformation through four phases: digitisation and automation of legal processes, code-based regulation, and blockchain-enabled smart contracts that formalise and autonomously enforce contractual terms. This trajectory exemplifies how code, once a tool to support legal enforcement, progressively assumes the law's characteristics (De Filippi and Hassan, 2016).

Berdos contribute to the discourse by identifying critical knowledge gaps in integrating blockchain and additive manufacturing, particularly the unresolved issue of certification authorities and hardware-level integration challenges (Berdos, Vele and Dounas, 2023, pp. 709–718). The paper highlights the misalignment of incentives among designers, customers, and makers, noting that fabricators bear the highest costs with limited direct benefits. To address this, the authors propose a four-tier workshop classification system to incentivise fabricators and balance stakeholder interests. Additionally, the study introduces a decentralised marketplace model that leverages blockchain to enhance transparency, trust, and coordination within distributed manufacturing ecosystems.

Alkhader describes a system leveraging Ethereum and IPFS for end-to-end traceability and certification of 3D printed products (Alkhader et al, 2020, pp. 188363–188377). Their architecture includes an Ethereum smart contract facilitating transactions between stakeholders—customers, 3D printing workshops, digital product managers, and a certification authority. All process data, including designs, IoT-collected print data, and videos of the final product, are stored on IPFS for authenticity verification. However, a key issue remains unresolved: who will act as the certification authority responsible for validating the final product and the operational processes? The paper raises concerns about the feasibility of universally upgrading existing desktop 3D printers to comply with the required hardware specifications for certification.

Additionally, Holland proposes using physical security elements (e.g., RFID, holograms, security pigments) embedded during the printing process to authenticate the origin and integrity of the printed object (Holland, Nigischer and Stjepandić, 2017, pp. 914–921). This complements blockchain's role by providing tangible certification elements that printers can automate, reducing human interference and the risk of counterfeiting. Moreover, Kurpjuweit points out that blockchain can certify digital and physical assets, enhancing trust through a decentralised system (Kurpjuweit et al, 2021, pp. 46–70). However, a central certification entity or protocol for universally certifying 3D-printed objects remains a gap in the current state of research.

Integrating decentralised technologies such as blockchain with 3D printing presents a promising yet complex pathway toward resolving certification, traceability, and stakeholder coordination challenges in additive manufacturing. While existing research demonstrates significant progress in digital trust mechanisms and regulatory frameworks, especially in high-tech realms, critical gaps remain, particularly in establishing universally accepted certification authorities and ensuring hardware-level compliance. These unresolved issues underscore the need for further technical refinement in 3D printing processes, especially in high-stakes applications like 3DCP. As the discussion shifts toward technical implementation, the next section examines the

material and procedural innovations shaping 3DCP, focusing on rheological control, layer adhesion, and the evolving standards governing printable concrete mixtures.

RESEARCH QUESTIONS AND AIMS

This research aims to define the theoretical framework for creating a decentralised system for defining standards and their distribution among all stakeholders of the 3DCP pipeline.

This paper addresses the following research questions:

- What methodologies can be identified as suitable for knowledge transfer?
- Which workflow allows for defining standards and sharing and validating parameters?

REVIEW OF METHODOLOGIES

The proposed theoretical regulatory framework relies on DLTs and decentralised systems operating in two stages, initially for data collection and standards definition and finally for the safe and reliable distribution of standards and validation of 3DCP processes.

Decentralised Ledger Technology offers significant advantages for managing, analysing, and validating 3DPC design and mechanical parameters by ensuring transparency, immutability, and traceability across the entire process. By recording all design iterations, material properties, and performance data on a distributed ledger, stakeholders can collaboratively verify and refine parameters, fostering trust and consistency. This decentralised approach enables the creation of a robust, auditable regulatory framework, as the aggregated data forms an evidence-based foundation for establishing standardised 3DCP practices, ensuring safety, quality, and interoperability in the industry.

The first stage consists of a decentralised benchmarking of materials, with the primary goal of gathering data on the controlled production of specimens and the corresponding mechanical test results. Under the supervision of institutional stakeholders in charge of regulations, a network of research labs with equivalent facilities and technologies is established. Material science, robotics, computational design, and engineering are the main disciplines involved in the design and realisation of benchmarking. The resulting dataset is analysed to extract patterns and correlations between production parameters and mechanical performance.

In the second stage, standardised specimens are 3D printed by getting the production parameters from the decentralised dataset to verify that the resulting performance aligns with the analysis conducted during the first stage.

Implementing this theoretical framework relies on effectively transferring information among multidisciplinary teams and establishing a decentralised system capable of creating a large dataset and sharing and validating information.

Knowledge transfer methodologies

The decentralised infrastructure, the geographically scattered research network, and the multidisciplinary task force require information and knowledge to be shared in an efficient way.

Knowledge transfer across different engineering domains is critical for fostering innovation and improving collaboration among multidisciplinary teams. Various methodologies have been proposed to facilitate this transfer, reflecting different theoretical frameworks and practical applications relevant to engineering education, management, and technology.

One effective approach to knowledge transfer involves ontology engineering methodologies, which focus on structured representations of knowledge. For instance, the DILIGENT framework facilitates knowledge sharing among geographically dispersed groups by emphasising the argumentation process essential for agreeing on updates for shared ontologies (Tempich et al,

2007, pp. 52–59). These methodologies support collaboration between domain experts and ontology engineers, streamlining knowledge management in applications spanning multiple engineering domains.

In another innovative direction, the KNOMAD (Knowledge-Based Engineering: Multidisciplinary Implementation) methodologies have emerged to effectively synthesise knowledge from different engineering contexts. This approach integrates knowledge management with engineering practices to create a systematic framework that allows applying insights from one domain to solve problems in another (Curran et al, 2010, pp. 7336–7350).

The role of knowledge management systems further underscores the methodologies for transferring knowledge. CommonKADS, SPEDE, and MOKA are established methods within the domain of knowledge engineering, often emphasising the importance of model suite and template knowledge for effective problem-solving (Sureephong et al, 2007, pp. 2041–2045). By applying these structured approaches, engineering teams can translate insights from one area, such as software engineering, to manufacturing or system design practices.

Transfer learning is another prominent methodology in engineering domains, particularly in machine learning contexts. This technique enables the application of models trained on one domain (the source) to improve performance in another (the target), capitalising on the inherent similarities between domains (Kim and Youn, 2019, pp. 46917–46930). The transfer of knowledge in fault diagnosis illustrates this approach, where models can be adapted from one engineering system to another with differing characteristics, enhancing diagnostic capabilities even with limited data (Lei, 2019, pp. 1–8).

Finally, frameworks addressing the socio-technical aspects of engineering projects highlight the importance of interpersonal dynamics in knowledge transfer. Studies indicate that incorporating factors such as team interaction, cultural context, and shared objectives significantly influences the effective transfer of knowledge among engineering participants (Cheng and Li, 2012, pp. 2156–2159). Introducing resident engineers within organisations has improved such transfers by facilitating communication and speeding up decision-making processes related to modifications and innovations (Mateo, Tanco and Santos, 2011, pp. 40–52).

In conclusion, the methodologies for transferring knowledge across engineering domains are diverse and multifaceted, encompassing structured approaches such as ontology engineering, practical frameworks like KNOMAD, advanced techniques like transfer learning, and considerations of social dynamics. Each of these methodologies is vital in enhancing collaboration, fostering innovation, and solving complex engineering problems effectively.

Ontology engineering

Within the domain of ontology engineering, creating ontologies for defining knowledge and representing it in a machine-readable format compatible with the semantic web is an established technique. We elected to model first the simple, high-level ontology before configuring a detailed system, as the resources required for full deployment (at least two laboratories and a full set of blockchain smart contracts) so that we establish the first knowledge management principles before deploying the infrastructure. This also allows for a modular architecture and flexibility in deployment while still maintaining compatibility with our theoretical model. This ontology has been created to capture the knowledge needed to create a decentralised 3D printing network with a dual purpose: Defining global standards (i.e. knowledge) for concrete 3D printing and operationalising this first network. A third aspect, which is using such a network to produce building components, remains a further

stretch goal step. The domain includes additive manufacturing as a process and decentralised ledger technology/blockchain. The scope of the ontology is to represent relationships and knowledge in the decentralised fabrication network for determining standards of performance for 3DPC.

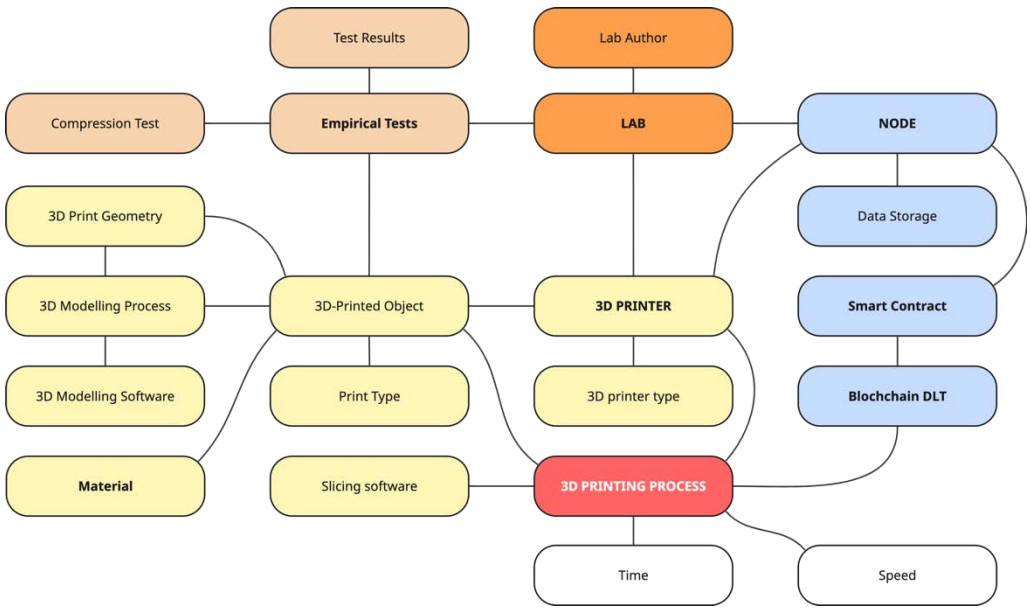

Figure 1
Proposed decentralised standardisation framework

Ontology creation is a design exercise and, as such, does not have a singular predetermined process. However, we consulted existing ontologies on additive manufacturing, such as those by Han (Han and Schaefer, 2019, pp. 850–855) and by Sanfilippo (Sanfilippo, Belkadi and Bernard, 2019, pp. 182–194). While our Ontology follows established paths, it diverges in introducing a decentralised infrastructure for managing the knowledge and information related to additive manufacturing production. Conceptually, the decentralised infrastructure replaces, for example, a centralised cloud infrastructure that could be used to manage disparate 3d printers geographically distributed.

Decentralisation through the introduction of blockchain technologies shifts trust to the computing protocol and establishes traceability of the information, automatic compliance through smart contracts, real-time logging and tamper-proof certification. In that sense, information recorded through empirical tests in the 3d printing network can be scientifically validated by other labs or scientists or even challenged in terms of its performance. The introduction of smart contracts entails the idea of incentives, which might allow for a much more equitable participation in the common pool of knowledge.

DECENTRALISED FRAMEWORK SETUP

The proposed decentralised standardisation framework (ontology) is illustrated in Figure 1. The lab is an authenticated user of the

decentralised system. Initially, a restricted number of selected labs will be part of the network and operate under strict control of production parameters to provide reliable information and data. Once the decentralised framework has demonstrated its efficacy, the system will be open to voluntary self-registration from other 3DCP laboratories, opening a new phase of testing and reliability checks.

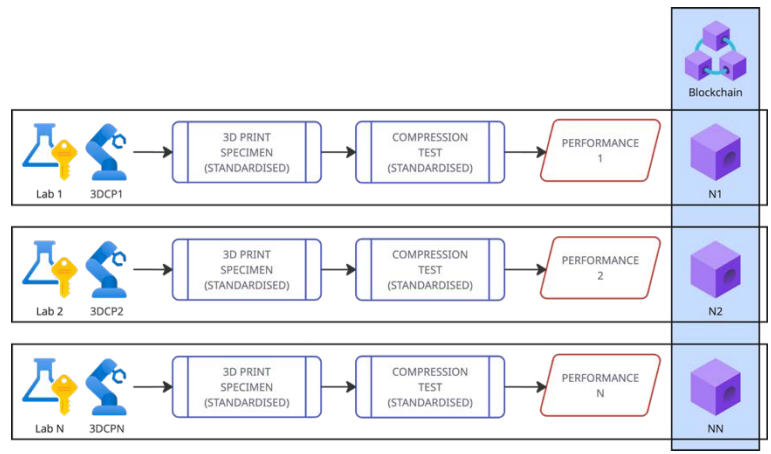

Figure 2
Stage 1 – knowledge gathering and definition of standards

A network of labs with equivalent 3DCP pipelines and testing units is connected to a decentralised system. The 3D printing hardware might consist of large-format gantry 3D printers or robotic arms with concrete extruders; this hardware requires dedicated standardisation (*ISO/ASTM 52939*, 2023). The graph shows a preliminary set of dimensions involved in defining parameters and standards. The first deployment of the decentralised system will aim to standardise the material (ink) and benchmark its mechanical performance, allowing for testing and fine-tuning the system.

During the first stage (Figure 2), the labs implement standardised 3DCP of specimens and standardised compression tests (Adamtsevich, Pustovgar and Adamtsevich, 2021, pp. 141–148; Ley-Hernández and Feys, 2020, pp. 228–236), measuring the specimens' mechanical performance (i.e., compression strength). Production parameters will be tracked and annotated, including materials formulation, environmental conditions, software and hardware settings, curing conditions, and testing settings. Production parameters are then uploaded to the blockchain together with the recorded mechanical performance of the 3DPC specimen, contributing to creating a large dataset and defining patterns of mechanical performance related to production parameters. The most efficient way of analysing the dataset will be to use a pre-trained AI fine-tuned on 3DCP applications.

Stage 2 will consist of sharing and validating the production parameters and mechanical performance of 3DPC specimens (Figure 3). The production parameters, customised for the specific 3DCP pipeline, are downloaded from the decentralised system by the labs. With the adoption of the same standardised 3DCP and mechanical testing of specimens, the goal is to obtain the same mechanical performance from each lab. The mechanical performance of 3DPC will be assessed with reference to existing concrete grade standards.

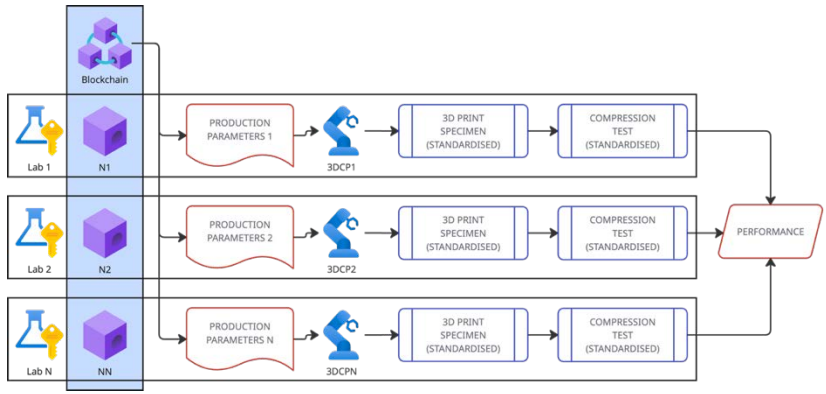

Figure 3
Stage 2 – sharing of standards to obtain controlled 3DPC performance

By analysing the dataset and the emerging patterns, it is possible to detect the best combinations and, therefore, define standards. The knowledge transfer methodology (Kim and Youn, 2019, pp. 46917–46930) will allow each lab's information (knowledge) to be inferred as valid in the process and results replicated in other labs.

DISCUSSION AND CONCLUSION

Establishing a regulatory framework for the standardisation and industrialisation of 3DCP is essential for the extensive adoption of this technology in the construction industry. The proposed decentralised standardisation, sharing and validation system helps accelerate this process by connecting several 3DCP labs in a joint effort and under the same controlled conditions, contemplating a diverse set of localised production conditions, and potentially making a large set of validated data available for defining standards. Balancing global standards (e.g., ISO) with local adaptations remains challenging, but adopting a decentralised infrastructure seems to offer the necessary flexibility and the possibility of creating a layered set of standards: the core standards applicable in general and specific standards differentiated by geographic location, special 3DPC performance requirements, or local regulations (e.g. seismic areas).

There are some concerns about the definition of standards for industrial 3DCP applications due to the lack of information regarding the lifecycle analysis of 3DPC structures: as of now, very little information is available on this matter, as few large-scale 3DPC constructs have been built worldwide. Another area to explore comes from the cybersecurity in DLTs: a decentralised regulatory framework would require a robust and redundant safety infrastructure to avoid introducing biased or false data and the unauthorised use of data.

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