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DECENTRALIZED DATA MANAGEMENT IN AEC: NFT AND DIGITAL TWIN FOR ENHANCED DATA SHARING – dDT PLATFORM

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Abstract: The sustainable and efficient management of the built environment is a crucial challenge in the increasingly digitalized AEC sector. Innovative technologies such as Building Information Modeling (BIM) and Digital Twin (DT) offer significant opportunities to enhance the operational efficiency and sustainability of physical assets. However, digitalization generates vast amounts of Big Data, and their handling through centralized architectures leads to risks of fragmentation, lack of transparency, and vulnerability to manipulation. In response to these challenges, this study presents an innovative Proof of Concept (PoC) that integrates Blockchain (BT), Digital Twin (DT), and Non-Fungible Token (NFT) technologies to promote decentralized and sustainable data management in the construction industry. The application, called dDT (decentralized Digital Twin), was initially deployed on the Solana blockchain and later integrated with Polygon to leverage EVM compatibility and the ERC-721 standard for NFTs. The platform enables the tokenization of data flows generated by physical assets, ensuring traceability, security, and transparency throughout the entire asset lifecycle. The dDT system represents a sustainable innovation as it creates a secondary data market, fostering collaboration among industry stakeholders and financing new developments through the sale of data-linked NFTs. This decentralized solution addresses fragmentation and transparency issues, promoting more secure, resilient, and sustainable data management practices. The PoC demonstrates how the integration of BT, DT, and NFT can accelerate the transition toward more efficient and innovative practices, with positive impacts on sustainability and technological advancement in the AEC sector.

Keywords: Construction, Data management, Digital Twin, Blockchain, NFT

1. INTRODUCTION: DIGITALIZATION AND CHALLENGES IN THE AEC SECTOR

The construction industry is increasingly embracing digital technologies to enhance the sustainability and efficiency of the built environment. Building Information Modeling (BIM) and Digital Twin (DT) have emerged as promising solutions, offering opportunities to optimize asset performance throughout their lifecycle (Hosamo et al., 2022). However, the fragmented nature of the industry and the exponential growth of data generated by these technologies pose significant challenges in terms of transparency, data ownership, and vulnerability to manipulation. (Nawari & Ravindran, 2019a). To address these issues, this study presents a Proof of Concept (PoC) that integrates Blockchain (BTC), DT, and Non-Fungible Token (NFT) technologies to create a decentralized and sustainable data management platform, called dDT (decentralized Digital Twin) (Hemdan et al., 2023). The dDT system enables the tokenization of data flows generated by physical assets, ensuring traceability, security, and transparency across the entire asset lifecycle. The platform was initially deployed on the Solana blockchain and later integrated with Polygon to leverage EVM compatibility and the ERC-721 standard for NFTs. The decentralized nature of the dDT platform promotes collaboration among industry stakeholders and creates a secondary data market, where data-linked NFTs can be traded to finance new developments. This innovative solution addresses the fragmentation and transparency issues plaguing the AEC sector, fostering more secure, resilient, and sustainable data management practices with positive impacts on sustainability and technological advancement. The paper is structured into several sections. The introduction outlines the main emerging technologies in the AEC industry and the related challenges, framing BTC as a potentially viable tool for the secure and decentralized management of big data. Next, an implemented method inspired by the framework developed by Naderi and Shojaei (Naderi & Shojaei, 2024) is presented, structured in five main phases, including the PoC, followed by the obtained results, a critical discussion of the results, and final conclusions.

1.1 The growing digitalization and the opportunities offered by innovative technologies

The digital transformation of the AEC sector is characterized by the synergistic implementation of innovative interconnected technologies such as BIM and DT. Research by Sacks et al., (Sacks et al., 2020a) highlights how, unlike BIM which provides a static representation of the building, DT integrates data from IoT sensors, building automation systems and other sources to create a model "living" virtual environment that constantly reflects the current state of the building. The integration of these technologies with Artificial Intelligence (AI) systems has further enhanced their capabilities. Pan and Zhang (Pan & Zhang, 2021) demonstrate how Machine Learning (ML) algorithms, by analyzing historical and real-time data provided by DT, can identify behavioral patterns of buildings and predict maintenance needs with considerable accuracy. However, this digital transition generates significant challenges in data management, which will be analyzed in the next section.

1.2 Challenges related to big data management

The increasing digitalization in the AEC sector, driven by the adoption of BIM and DT, generates significant volumes of heterogeneous data that present complex management challenges. Tang et al., (Tang et al., 2019) identify how the nature of big data in construction is defined by the "5V": (i) volume (amount of data generated); (ii) velocity (speed of generation and need for real-time processing); (iii) variety (diversity in sources and formats); (iv) veracity (accuracy and reliability), and (v) value (utility of extracted information). Centralized data management, however, has notable limitations. First, fragmentation of information across various stakeholders and platforms hinders interoperability and operational efficiency. Lu et al., (Lu et al., 2018) demonstrate that data integration and synchronization from diverse sources remain major challenges, significantly impacting productivity and project costs. Security is another critical concern; centralized architecture creates single points of failure vulnerable to cyber-attacks. Research by Teizer et al., (Teizer et al., 2017) shows that the increasing digitalization in AEC has led to a rise in cybersecurity vulnerabilities, particularly concerning the protection of sensitive data and critical infrastructure security. Data ownership is yet another pressing issue. Nawari and Ravindran., (Nawari & Ravindran, 2019b) analyze how, in a digital ecosystem with multiple contributors to data generation and usage, clear definitions of data ownership and access rights are essential. A lack of transparency in data management can lead to conflicts among stakeholders and impede effective collaboration. Additionally, centralized control over data can enable information manipulation, compromising decision-making integrity. Privacy also poses significant challenges, especially given the sensitive nature of data collected in smart buildings. The absence of standardized data management and sharing protocols, combined with organizational resistance to change, further hinders widespread adoption of these technologies.

1.3 Blockchain and NFTs towards decentralized data management

Blockchain technology is emerging as a promising solution to tackle data management challenges in the AEC sector, offering a decentralized architecture that ensures transparency, immutability, and security. Elghaish et al., (Elghaish et al., 2021) highlight blockchain as a distributed ledger where transactions are organized into cryptographically protected, interconnected blocks, providing data immutability and transparency without the need for centralized intermediaries. Next-generation blockchains like Polygon (Polygon whitepaper, 2021) and Solana (Solana whitepaper, 2020) offer significant improvements over traditional platforms. Polygon, built on Ethereum's Layer-2 architecture, offers high scalability and reduced transaction costs while maintaining compatibility with the Ethereum Virtual Machine (EVM). Meanwhile, Solana employs an innovative Proof of History (PoH) consensus mechanism, enabling up to 65,000 transactions per second with minimal latency. These features are critical for handling the high data volume generated by DT and BIM systems. The integration of NFTs marks a significant innovation in AEC data management. NFTs, unique cryptographic tokens based mainly on the ERC-721 standard, allow for the tokenization of data streams from physical assets, creating a unique, verifiable digital representation of information. This tokenization facilitates the creation of a secondary data market where information can be securely and transparently exchanged, opening new monetization avenues. Smart contracts (SC), self-executing programs operating on the blockchain, automate data access rights and sharing. This automation can potentially reduce transaction costs and enhance the efficiency of data management processes. However, significant challenges must be addressed to enable adoption. Hunhevicz and Hall (Hunhevic & Hall, 2020) identify critical parameters for selecting and implementing blockchain solutions, such as: (i) System scalability to accommodate AEC data volumes; (ii) Energy efficiency of consensus mechanisms; (iii) Interoperability with existing systems and across different blockchains; (iv) Economic sustainability, including operational and implementation costs; (v) Security and reliability of validation protocols. The primary challenges, as Sacks et al., (Sacks et al., 2020b) point out, also include developing shared standards for data interoperability and privacy management, as well as balancing transparency with the confidentiality of sensitive information.

2. METHOD

The following chapter describes the methodological process implemented starting from Naderi and Shojaei (Naderi & Shojaei, 2024) and used for the development of the PoC of the project, structured in five main phases. The first phase involves problem identification, highlighting how data management in the AEC sector is affected by fragmentation and a lack of transparency. The increasing digitalization of the sector has led to the generation of vast amounts of data, often managed inefficiently due to centralized and vulnerable solutions. These issues compromise efficiency and security, especially in the traceability and management of information flows throughout the lifecycle of built assets. The need for a more secure, transparent, and decentralized approach to address these challenges drove the development of the proposed solution. The second phase focuses on defining the solution's characteristics, based on the integration of BCT, DT, and NFT technologies. This solution will be applied throughout the entire asset lifecycle, from design to decommissioning, enhancing decentralized data management and ensuring security and traceability through the tokenization of information flows. This approach allows for more efficient asset control, ensuring that data remains accessible and protected during every stage of the lifecycle. In the third phase, the framework of the platform was designed Naderi and Shojaei (Naderi & Shojaei, 2024), developing a structure capable of integrating off-chain components (such as sensor and data management) with on-chain components (secure data registration on the blockchain). This framework was conceived to ensure seamless integration of technologies and to improve the real-time management and sharing of data. The fourth phase involved the development and implementation of the PoC, initially on the Solana blockchain and later on Polygon. The migration to Polygon was motivated by the establishment of well-recognized standards for NFTs, such as ERC-721, the compatibility with the Ethereum Virtual Machine (EVM), and the existence of a more advanced development ecosystem compared to Solana. This larger developer community allowed for greater interaction, feedback, and the benefit of a higher number of existing projects, facilitating the development of the dDT platform. Finally, in the fifth phase, the evaluation of results was conducted, analyzing the key parameters for comparing the three blockchains under consideration: Ethereum, Solana, and Polygon. The parameters evaluated include throughput, transaction costs, security, scalability, and community development support. These elements allowed the identification of the strengths and weaknesses of each network, enabling an informed decision for the dApp implementation.

2.1 Proposed solution

The proposed solution covers the entire life cycle of a built asset, from conception to decommissioning, by integrating BCT at all relevant stages. The image below clearly illustrates the main phases of the physical asset's life cycle (PT) and its digital counterpart (DT), highlighting how key information from each phase is recorded and protected on the blockchain. This integration ensures efficient and secure data management, improving transparency, traceability, and trust among professionals throughout the asset's life cycle. The first step in the blockchain involves the creation of an NFT that represents the project (NFT-parent). This NFT acts as a container for the sub-NFTs (or "child" NFTs), i.e. the documents that will be generated in the different phases of the project, ensuring secure and traceable information management. For each phase, specific documents are chosen as examples: (i) in the design phase, the "BIM design-built" model is tokenized; (ii) in the construction phase, the "BIM as-built" model; (iii) in the maintenance and operation phase, a maintenance report and sensor data (e.g., data exceeding a specified tolerance threshold) are tokenized; (iv) in the decommissioning or archiving phase, the archived DT is tokenized. These examples serve to clarify the concept, but the actual documents may vary depending on the project and the requirements of each phase. Each NFT created will have a timestamp, ensuring the traceability and immutability of the recorded information. A crucial aspect of the DT is that it is never deleted. When the physical asset is decommissioned, its corresponding DT is archived and becomes a valuable source of information for future projects and professionals in the AEC sector. The DT continues to exist independently of the PT, acting as a permanent knowledge repository. In this sense, the physical asset can be compared to a human being that is born, grows, and eventually ceases to exist, while the DT is like accumulated wisdom that persists and provides valuable insights for the future.

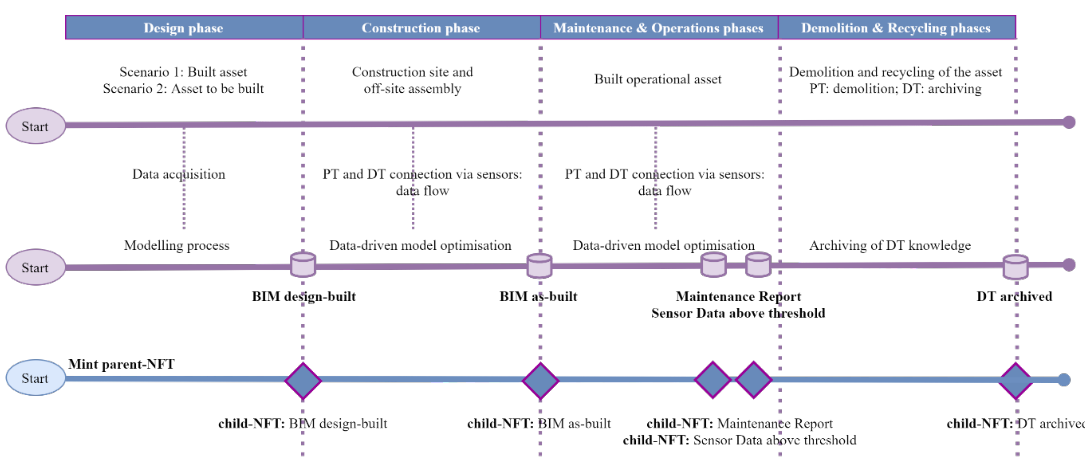

Figure 1 - Integration of blockchain technology into the building process

2.1.1 Logic of the NFT structure

The PoC is based on a "parent-child" NFT mapping structure. The "parent" NFT or "project" NFT represents the reference construction project and is created when a new project is initiated on the dDT platform. This "parent" NFT functions as a dynamic container of information, continuously updating based on the documents that are tokenized and added to the blockchain. The "child" NFTs or "sub-NFTs" represent the individual documents, data, and relevant information associated with the project, recorded on the blockchain. These sub-NFTs are static and closely linked to the "project" NFT, as they are tied to a specific project.

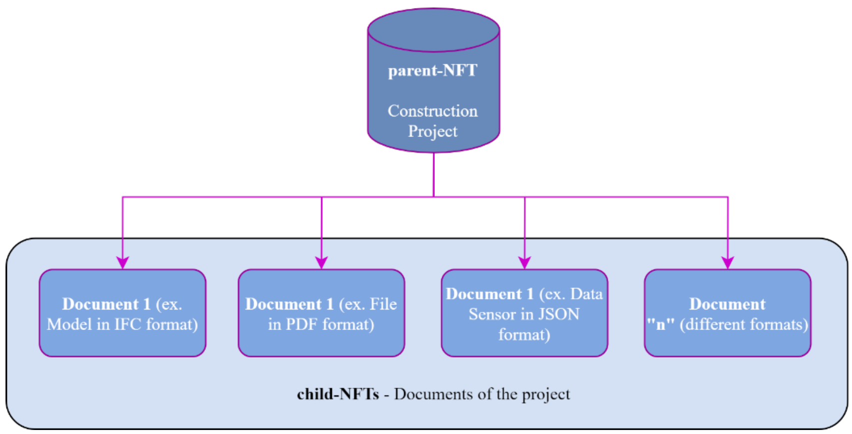

Figure 2 - Parent-child mapping of NFTs

2.2 Design framework

The integration of DT, BCT, and NFT aims to enhance project management in the construction sector. DT are virtual representations of physical assets in construction, powered by data from various sources throughout the entire project lifecycle. BCT provides the essential infrastructure for this system, offering a decentralized, immutable, and transparent network, ideal for hosting SC and ensuring the security and traceability of information. In this context, NFTs play a crucial role as unique digital assets used to represent the data associated with DT. Each NFT enables a clear definition of data ownership, facilitating secure management and precise control of information among the involved stakeholders. The proposed framework, implemented starting from Naderi and Shojaei (Naderi & Shojaei, 2024) is applied to a civil infrastructure project, and is designed to be adaptable to any other type of project. It is divided into two distinct layers: off-chain and on-chain, each characterized by different components. The following figure clearly illustrates the components of these two layers.

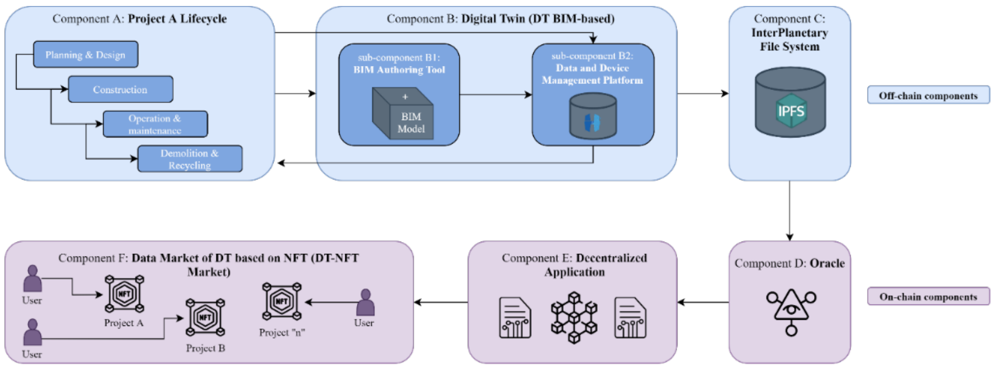

Figure 3 - Design Framework implemented from Naderi & Shojaei, 2024

2.2.1 Off-chain components

The off-chain components are the elements of the system that operate outside of the blockchain. Although they are separate from the blockchain network, they interact with it to ensure efficient management of data and processes related to the project. The components are: (A) Project Lifecycle; (B) Digital Twin (DT BIM-based); and (C) InterPlanetary File System (IPFS).

The first component of the framework, Project A Lifecycle, concerns the life cycle of the digitized physical asset and the documentation connected to it. The physical asset is an arch bridge located in Montebello Vicentino in Italy, which represents the pilot case study. The second component of the framework, the DT (based on DT BIM), is a digital representation of the physical asset created from a BIM model. Although not a fully operational DT, the framework takes a methodical approach inspired by industrial cycles, where, before implementing a system in a real-world context, simulations are conducted in the laboratory to test, refine and engineer the model. Simulated data from a similar asset feeds the platform to test and tune the model, demonstrating its ability to interact with sensors and physical assets. To implement this process, two subcomponents were used: (B.1) a BIM creation software, Tekla Structures (Trimble Connect), for creating the BIM model; and (B.2) a data and device management platform, ACSoftware's HyperIoT, for data and device management. This approach is crucial to validate the system and facilitate future integration of bidirectional flows between DT and real goods. The third component of the framework, the InterPlanetary File System (IPFS), is a distributed file storage and sharing protocol, designed to create a decentralized system in which data is stored across a peer-to-peer network (P2P). Instead of relying on a central server, IPFS distributes files across various nodes on the network, increasing resilience, speed and security. In the blockchain context, IPFS is used to store large amounts of data, such as project files, BIM models, and sensor data. The blockchain stores a link in the form of a unique hash that points to the content on IPFS, ensuring that the data remains unchanged. By accessing the file via the hash, IPFS recovers the distributed content, ensuring its accessibility and auditability.

2.2.2 On-chain components

On-chain components are the elements of the system operating within the blockchain, ensuring the security, transparency, and immutability of data. These components are fundamental for the integration and management of information and processes related to the project. They include: (D) Oracle; (E) dApp (Blockchain and Smart Contract); (F) Data Market of DTs based on NFT (DT-NFT Market).

The fourth component of the framework, the oracle, allows the blockchain to interact with data external to its ecosystem, acting as a "bridge" between the real world and the decentralized network. It collects information from external sources, such as sensors and APIs, and transmits it securely and verifiable to the blockchain. This data can come, for example, from the sensors of a physical asset. Furthermore, the oracle allows the blockchain to automatically respond to external events by activating smart contracts that perform predefined actions based on the data provided. The fifth component of the framework is the dApp, called Decentralized Digital Twin (dDT). It is the central element of the project and represents a decentralized platform designed to manage DT of physical assets. By exploiting blockchain technology, it guarantees data security, traceability and transparency. The dApp enables the tokenization of relevant information, such as models, sensor measurements, maintenance reports, etc., through the use of NFTs. The implementation of the dDT dApp is currently being developed on two blockchains, Solana and Polygon, each with specific technical characteristics and libraries. The sixth and final component of the framework is a secondary data market based on NFTs, designed to represent the knowledge associated with DTs. This marketplace brings together various projects related to the existing built environment, allowing the sharing and exchange of information generated by individual projects. The progressive growth of the market will make the most relevant data of a project accessible, allowing the professionals involved and beyond to download them, albeit with some limitations. Not all professionals will have full access to the data: viewing and downloading of data will be regulated based on the results of future research. Based on tests conducted on real projects, these studies will define the accessible data for each professional category and specific criteria to justify such restrictions. The main advantage of this market is represented by the decentralized data management, which allows all the advantages of decentralization, including immutability, transparency, historical traceability and clear attribution of responsibility to the professionals involved. Furthermore, sharing data, including models, reports, sensor data, etc., offers other AEC professionals the opportunity to improve their skills, thus accelerating the progress of the industry and promoting the creation of increasingly advanced models. The following figure illustrates the structure of the data market connected to the dApp, with the representation of the various NFTs (sub-NFTs) associated with the different projects (NFT project) through a parent-child mapping logic. Each project includes multiple files, which are tokenized as sub-NFTs or "child" NFTs, and can be shared and downloaded in accordance with restrictions established by future research and testing. In the paragraph relating to the PoC, the stakeholders identified for interaction with the market will also be described and the different data access fees envisaged based on their role through simplified identification.

2.3 Proof-of-Concept

The PoC outlines the activities conducted on HyperIoT, aimed at testing the platform's capabilities in managing sensors and the data derived from them, in preparation for future integration of critical or relevant data into the dApp for historical record-keeping. Additionally, it presents the frontend design through a flowchart and the operational logic of the proposed DT-NFT Market, with particular attention to user interaction methods and data acquisition and management strategies.

2.3.1 Activities carried out within the Data and Device Management platform

The activities carried out on HyperIoT include: (i) BIM model import; (ii) model sensorization based on simulated data; (iii) configuration of tolerance thresholds to identify critical data; (iv) export of identified critical data and import into the dApp, where they are tokenized as sub-NFTs associated with the project's main NFT.

Figure 4 - BIM Model from Tekla Structures to HyperIoT

2.3.2 Conception of the dApp dDT front-end

The dDT dApp was conceived starting from the creation of a flow diagram (Figure 10) that showed the various steps necessary for recording project data in the BC. The diagram is organized into three different sections represented with different colours: (A) the first with the blue color concerns access to the BC; (B and C) the second with the yellow color concerns access to the dDT dApp, this is further divided into a section concerning the projects and therefore the creation of the parent-NFT (B) and a section concerning the documents associated with that project therefore inherent to the creation of child-NFTs (C); (D) the last one with the red color concerns future implementations of the dDT platform. The dDT dApp was designed starting from a flowchart (Figure 10) that illustrates the various steps necessary to register project data in the BC. The diagram is divided into three sections, each represented by a distinct color: (A) blue for blockchain access; (B and C) yellow for access to the dDT dApp, which is further divided into a section dedicated to the projects, therefore to the creation of the parent-NFT (B) and into a section relating to the documents associated with the project, concerning the creation of the child-NFT (C); (D) red for future implementations of the dDT platform.

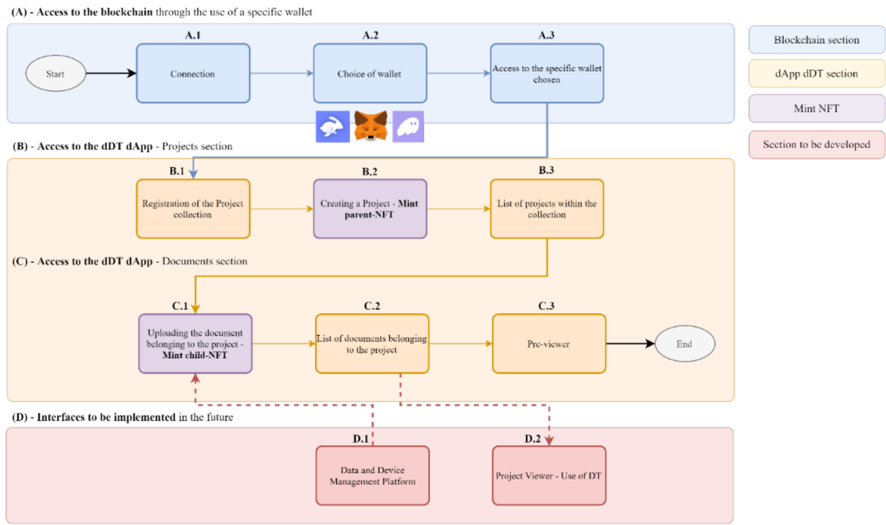

Figure 5 - Front-end conception of dDT dApp

2.3.3 Types of stakeholders and their interaction in the DT-NFT Market

The dDT dApp allows the management of projects and related documents through their registration on the BC in the form of NFT. The parent-NFTs, which represent the projects, act as containers for the child-NFTs, which represent the relevant documents appropriately registered in the BCT. Child-NFTs are often valuable sources of knowledge and, if released into a sharing and exchange circuit, can bring value to the AEC sector, contributing to its progress. The dApp involves interacting with a secondary market of DT data in the form of NFTs. This market, called DT-NFT Market, represents the last component of the framework, capable of valorising DTs through the diffusion of their knowledge. A potential barrier to information sharing is project managers' skepticism regarding responsibility for any critical issues. Overcoming this resistance will be crucial to improving oversight and transparency, which are critical to the industry's progress. Four main groups of stakeholders capable of interacting with the DT-NFT Market are identified.

1. **Stakeholders internal to the project:** These actors, which include the client, the general contractor, the designers, the construction company and the facility manager, are responsible for the different phases of the asset's life cycle. It is important to note that this categorization is simplified; in reality, the design involves numerous professionals specialized in different disciplines, contributing to a multidisciplinary model of the asset. Internal stakeholders will not have to pay fees for access to data, but may be subject to limitations based on the type of information. The definition of what data can be visualized and by whom will be the subject of future research, through the implementation of a real project in the dDT platform.
2. **Stakeholders external to the project but belonging to the AEC sector:** These stakeholders will have to request access to the data from the project manager and can benefit from acquiring information on the various projects. Acquiring knowledge accelerates skills and promotes the progress of the AEC industry. The fees for accessing the data vary based on the willingness of

the stakeholders to enter the knowledge exchange circuit. If they bring their own project to the platform, the data access fee will be reduced. The definition of which data can be sold and which is sensitive will be established on a case-by-case basis, however requiring the implementation of a real project.

3. **Supervisory authorities:** This category includes all the control bodies involved in the different phases of the project, such as verifiers and testers. The supervisory bodies will have free access to the data, ensuring the correct execution of the project processes and improving transparency and the definition of responsibilities among stakeholders.
4. **Private citizens:** Those wishing to request information on a specific asset must forward a request to the project manager via the dDT platform. If access is allowed, they will be able to acquire the data upon payment of a commission, which will be higher than that for external stakeholders, since the acquisition of knowledge by private individuals will not bring direct benefits to the AEC sector.

This categorization is simplified. In practice, the process is much more complex, with a variety of professionals involved. In the design phase, for example, there is not just one designer, but a series of specialists in disciplines such as architectural, structural and plant design MEP. Each professional contributes with their own skills, integrating the information necessary to create a complete and multidisciplinary model of the asset. Other figures can come into play in the subsequent phases of the project, expanding the network of responsibilities and skills. Interested stakeholders at different phases can upload documents and register them as NFT-children of a parent-NFT. For example, the designer can upload a design-built BIM, while the construction company, with its designers, uploads an as-built BIM. During the operational phase of the asset, the facility manager could upload a maintenance report and sensor data indicating malfunctions or critical issues. Also in this case, the figures and documents considered relevant for registration in the BC will be many more than the examples provided. The cash flows generated by stakeholders interested in purchasing the data will mainly be used to finance the project itself, with a small percentage reserved for the development of the dApp. Payments will take place in fungible tokens, in line with the blockchain used (for example, SOL for Solana or MATIC for Polygon). Stakeholders wishing to manage a project using this system based on data exchange and transparency will need to set up an initial fund to cover the costs of tokenizing the documents and necessary transactions. The documents and stakeholders mentioned have been simplified for demonstration purposes. In future developments, it will be necessary to integrate a real project into the dApp, identifying all the stakeholders involved and cataloging the data to be recorded on the BC. Some of this data may not be shareable, but it can still be tokenized to ensure its immutability and traceability, with access limited to supervisory authorities only. The implementation of a real project will allow us to collect concrete feedback from participants, facilitating system optimization and ensuring greater security and transparency. This approach lays the foundation for future development that accelerates industry skills, improves data management and creates new cash flows for construction projects.

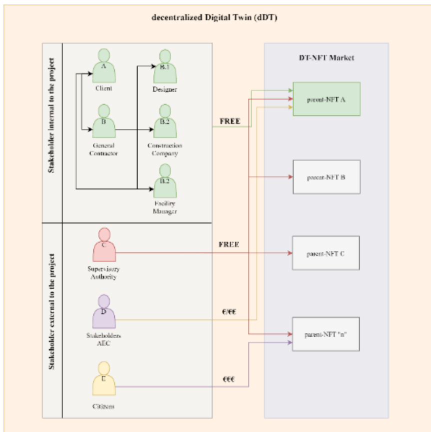

Figure 6 - Stakeholders access to the DT-NFT Markt based on roles

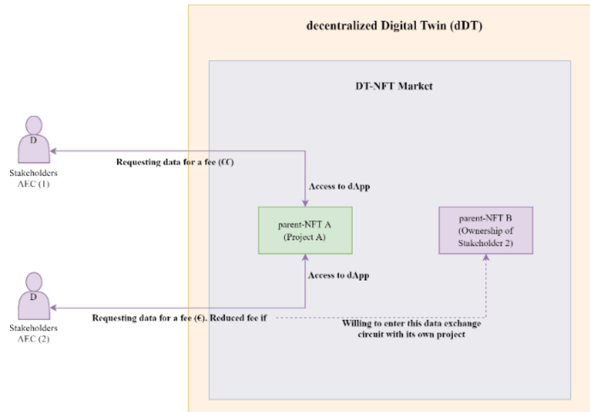

Figure 7 - Incentivising the use of the dDT platform for AEC stakeholders

2.4 Evaluation of blockchains

During the development of the project, a comparative analysis was conducted among three main blockchains: Ethereum (Ethereum whitepaper, 2013), Solana, and Polygon. The goal was to identify the most relevant features for our use case, focusing on essential aspects such as throughput, transaction costs, security, scalability, and developer community support. The analysis resulted in the creation of a comparative table that clarified the performance and potential of each blockchain in the context of our project, with particular attention to the needs related to decentralized data management and the integration of NFTs and DT. It is important to note that the comparative analysis is still ongoing to adapt to the evolving project requirements. Among the key parameters considered, throughput and transaction costs proved crucial in determining which blockchain could best meet the needs of our project. Ethereum, while being one of the most established and widely adopted blockchains, showed high transaction costs, making it unsustainable for our use. Its security and developed ecosystem were not sufficient to offset this drawback. On the other hand, Solana offered excellent characteristics in terms of throughput, with the capability to process thousands of transactions per second and very low transaction costs. Its technical performance and scalability make it an attractive choice, especially for projects requiring high efficiency and speed. However, it should be noted that Solana's developer community is still growing compared to more established blockchains. Ultimately, Polygon emerged as the optimal solution. Thanks to its compatibility with the Ethereum Virtual Machine (EVM) and already established standards, such as ERC-721 for NFTs, Polygon offers a high level of security with low transaction costs. Its excellent scalability, combined with a large developer community and a continuously expanding ecosystem, made this platform the ideal choice for the project. Nonetheless, Solana remains a viable option for the future. Once the project is implemented on Polygon, there will be an exploration of the possibility of creating a bridge between the two blockchains. Solana's outstanding performance in terms of speed and transaction costs makes it a promising solution for any future expansions.

3. RESULTS, LIMITATIONS AND FUTURE DIRECTIONS

The results of the implementation of the dDT platform highlight a first phase on Solana, chosen for its high performance and scalability, followed by the strategic migration to Polygon, compatible with Ethereum, to exploit consolidated standards such as ERC-721 and a more mature ecosystem. A distinctive aspect of the research is represented by the proposed incentive strategy, which provides for the reduction of commissions for stakeholders in the AEC sector willing to enter the circuit by contributing their own project, thus encouraging the adoption of the system. Tokenization, still new in the construction sector, was explored with an innovative approach: compared to existing theoretical and practical cases, such as Naderi's use of dynamic NFTs, the research introduced a hierarchical parent-child mapping of NFTs to track related projects and documents. The implementation on new generation blockchains such as Solana and Polygon demonstrates the technological validity, but the limitations highlighted underline the need for further practical applications and tests on real projects to consolidate the foundations laid, thus paving the way for future research and developments in the sector . The screenshots show the essential steps of the implementation on Polygon, to support the practical demonstration.

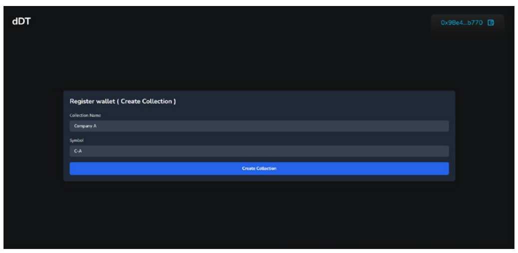

Figure 8 - dApp access and creating a collection of projects

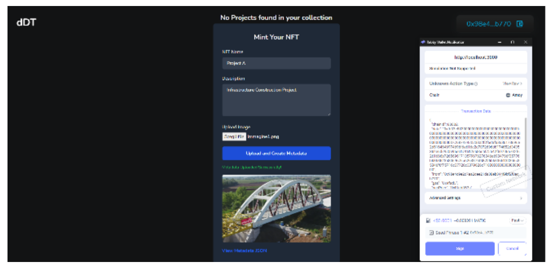

Figure 9 - Mint parent-NFT

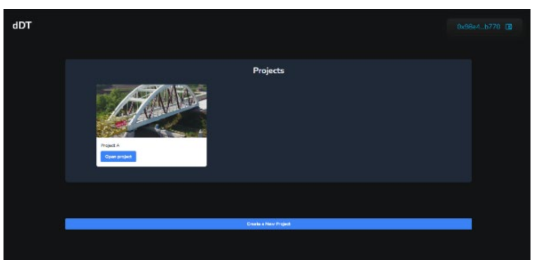

Figure 10 - Access to the created project

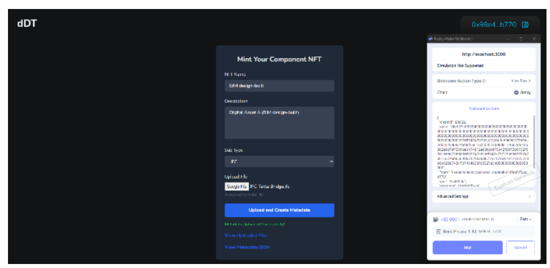

Figure 11 - Import a document (e.g. model) and Mint child-NFT

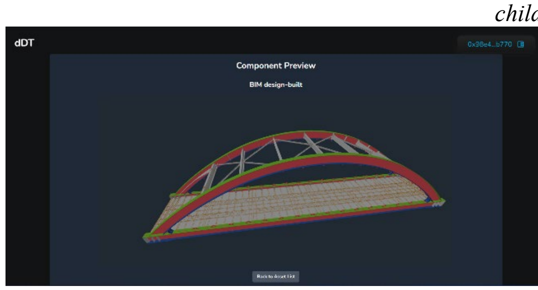

Figure 12 - Pre-viewer

5. CONCLUSIONS

The dDT (decentralized Digital Twin) platform emerges as a significant innovation to address data management challenges in the construction industry. By integrating advanced technologies such as BCT, DT and NFTs, the platform offers a solution to overcome structural problems, such as information

fragmentation, lack of transparency and the difficulty of ensuring traceability. The initial implementation on the Solana blockchain, followed by the migration to Polygon, highlighted the platform's ability to adapt to established standards and a more mature technology ecosystem. Polygon proved to be particularly suitable thanks to its compatibility with the ERC-721 standard, scalability and large developer community, ensuring an ideal environment for managing complex and dynamic data. A distinctive element of the project is the introduction of a hierarchical structure for the management of NFTs, with a parent-child logic. This approach allows project documents to be associated with a master NFT, facilitating transparent and secure management of information throughout the entire asset lifecycle. Furthermore, an incentive strategy has been developed to encourage the participation of industry professionals. Reducing commissions for those who contribute their own projects creates a virtuous cycle that encourages knowledge sharing and platform adoption. However, despite the promising results, the platform has some limitations. The absence of large-scale applications represents a barrier to consolidating the benefits that emerged from initial tests. Furthermore, cultural resistance to the adoption of innovative technologies by AEC sector stakeholders and the need for a clearer definition of sensitive data and access methods require further investigation.
Looking to the future, integrating a real project into the platform represents a crucial step in gathering concrete feedback, optimizing functionality and ensuring greater security and transparency. Expanding towards bidirectional management of data flows between physical assets and DT promises to further broaden the platform's applications. Furthermore, the creation of a secondary market for tokenized data opens up new economic opportunities, facilitating project financing and accelerating the technological progress of the sector. Ultimately, the dDT platform presents itself as an innovative solution for the digitalisation of the construction sector, promoting sustainability, collaboration between professionals and technological evolution. This project represents a solid foundation on which to build future developments that could improve the industry ecosystem.

REFERENCES

- Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction, 114*, 103179. https://doi.org/10.1016/j.autcon.2020.103179
- Buterin, V. (2013). Ethereum white paper: A next-generation smart contract and decentralized application platform. Ethereum Foundation. https://ethereum.org/en/whitepaper/
- Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction, 26*, 58-83. https://doi.org/10.36680/j.itcon.2021.005
- Elghaish, F., Hosseini, M. R., Matarneh, S., Talebi, S., Wu, S., Martek, I., Poshdar, M., & Ghodrati, N. (2021). Blockchain and the 'Internet of Things' for the construction industry: Research trends and opportunities. *Automation in Construction, 132*, Article 103942. https://doi.org/10.1016/j.autcon.2021.103942
- Hemdan, E. E., El-Shafai, W., & Sayed, A. (2023). Integrating Digital Twins with IoT-Based Blockchain: Concept, architecture, challenges, and future scope. *Springer Science+Business Media, 131*(3), 2193-2216. https://doi.org/10.1007/s11277-023-10538-6
- Hosamo, H. H., Imran, A., Cardenas-Cartagena, J., Svennevig, P. R., Svidt, K., & Nielsen, H. K. (2022). A review of the digital twin technology in the AEC-FM industry. *Hindawi Publishing Corporation, 2022*, 1-17. https://doi.org/10.1155/2022/2185170
- Hunhevicz, J. J., & Hall, D. M. (2020). Do you need a blockchain in construction? Use case categories and decision framework for DLT design options. *Advanced Engineering Informatics, 45*, Article 101094. https://doi.org/10.1016/j.aei.2020.101094
- Lu, Q., Chen, L., Lee, S., & Zhao, X. (2017). Activity theory-based analysis of BIM

implementation in building O&M and first response. *Automation in Construction, 85*, 317–332. https://doi.org/10.1016/j.autcon.2017.10.017

- Lu, Q., Parlikad, A. K., Woodall, P., Schooling, J. M., & et al. (2019). Developing a dynamic digital twin at building and city levels: A case study of the West Cambridge campus. *Journal of Management in Engineering, 36*(3). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000763
- Masciotta, M. G., Ramos, L. F., Lourenço, P. B., & Vasta, M. (2014). Damage detection on the Z24 bridge by a spectral-based dynamic identification technique. ISISE, University of Minho.
- Naderi, H., & Shojaei, A. (2024). Digital twin non-fungible token (DT-NFT): Enabling data ownership in the AEC industry. *Automation in Construction, 168*(A), 105777. https://doi.org/10.1016/j.autcon.2024.105777
- Nawari, N. O., & Ravindran, S. (2019a). Blockchain technologies in BIM workflow environment. https://doi.org/10.1061/9780784482421.044
- Nawari, N. O., & Ravindran, S. (2019b). Blockchain and the built environment: Potentials and limitations. *Journal of Building Engineering, 25*, 100832. https://doi.org/10.1016/j.jobe.2019.100832
- Pan, Y., & Zhang, L. (2020). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Automation in Construction, 113*, 103517. https://doi.org/10.1016/j.autcon.2020.103517
- Polygon Technology. (2021). Polygon: The Internet of blockchains. Retrieved from https://polygon.technology/whitepaper/polygon-whitepaper.pdf
- Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020b). Construction with digital twin information systems. *Data-Centric Engineering, 1*(e14). https://doi.org/10.1017/dce.2020.16
- Sacks, R., Girolami, M., & Brilakis, I. (2020a). Building information modelling, artificial intelligence and construction tech. *Developments in the Built Environment, 4*, 100011. https://doi.org/10.1016/j.dibe.2020.100011
- Solana Labs. (2020). Solana: A new architecture for a high performance blockchain. Retrieved from https://solana.com/solana-whitepaper.pdf
- Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in Construction, 101*, 127–139. https://doi.org/10.1016/j.autcon.2019.01.020
- Teizer, J., Wolf, M., Golovina, O., & König, M. (2017). Internet of Things (IoT) for integrating environmental and localization data in Building Information Modeling (BIM). In *Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC 2017)*, Taipei, Taiwan. https://doi.org/10.22260/ISARC2017/0084
- Trimble Connect: Trimble. (n.d.). Trimble Connect. Retrieved from https://connect.trimble.com/
- HyperIoT di ACSoftware: ACSoftware. (n.d.). HyperIoT. Retrieved from https://www.acsoftware.it/hyperiot/