Architecture and Planning Journal (APJ)

Volume 28 Issue 3 *ASCAAD 2022 - Architecture in the Age of the Metaverse – Opportunities and Potentials*
ISSN: 2789-8547

Article 20

March 2023

A CRYPTO-TWIN FRAMEWORK FOR THE AEC INDUSTRY - ENABLING DIGITAL TWINS WITH BLOCKCHAIN TECHNOLOGIES

THEODOROS DOUNAS
Robert Gordon University, United Kingdom, t.dounas@rgu.ac.uk

DAVIDE LOMBARDI
Xi'an Jiaotong - Liverpool University, China, davide.lombardi@xjtlu.edu.cn

JIRI VELE
Czech Technical University in Prague, Czech Republic, jiri.vele@cvut.cz

SIMON PROKOP
Czech Technical University in Prague, Czech Republic, simon.prokop@cvut.cz

Recommended Citation

DOUNAS, THEODOROS; LOMBARDI, DAVIDE; VELE, JIRI; and PROKOP, SIMON (2023) "A CRYPTO-TWIN FRAMEWORK FOR THE AEC INDUSTRY - ENABLING DIGITAL TWINS WITH BLOCKCHAIN TECHNOLOGIES," *Architecture and Planning Journal (APJ)*: Vol. 28: Iss. 3, Article 20.
DOI: https://doi.org/10.54729/2789-8547.1215

A CRYPTO-TWIN FRAMEWORK FOR THE AEC INDUSTRY - ENABLING DIGITAL TWINS WITH BLOCKCHAIN TECHNOLOGIES

Abstract

The paper describes a conceptual framework and the smart contract architecture for Crypto-Twins (CT) in the AEC industry, i.e. blockchain (BC) enabled digital twins. We describe the background, terminology of technologies involved, while the methodology follows design science research patterns to construct the framework and architecture of the Crypto-Twin. Further avenues for prototype development and validation of the framework are proposed in the conclusion.

Keywords

Blockchain, Digital Twin, Smart Contracts, Metaverse

A CRYPTO-TWIN FRAMEWORK FOR THE AEC INDUSTRY ENABLING DIGITAL TWINS WITH BLOCKCHAIN TECHNOLOGIES

THEODOROS DOUNAS[1], DAVIDE LOMBARDI[2], JIRI VELE[3], SIMON PROKOP[4]

[1] Robert Gordon University, United Kingdom
t.dounas@rgu.ac.uk

[2] Xi'an Jiaotong-Liverpool University, China
davide.lombardi@xjtlu.edu.cn

[3] Czech Technical University in Prague, Czech Republic
jiri.vele@cvut.cz

[4] Czech Technical University in Prague, Czech Republic
simon.prokop@cvut.cz

ABSTRACT

The paper describes a conceptual framework and the smart contract architecture for Crypto-Twins (CT) in the AEC industry, i.e. blockchain (BC) enabled digital twins. We describe the background, terminology of technologies involved, while the methodology follows design science research patterns to construct the framework and architecture of the Crypto-Twin. Further avenues for prototype development and validation of the framework are proposed in the conclusion.

Keywords: Blockchain, Digital Twin, Smart Contracts, Metaverse

ملخص

تصف هذه الورقة البحثية إطارًا مفاهيميًا وبنية لعقود ذكية للتوائم التشفيرية في مجال العمارة والهندسة والتشييد، أي التوائم الرقمية التي يتم تمكينها من خلال تقنية البلوكتشين. نصف فى هذا البحث الخلفيات ومصطلحات التقنيات المعنية، بينما تتبع المنهجية أنماط بحث علوم التصميم لبناء إطار لبنى التوائم التشفيرية. تم اقتراح المزيد من السبل لتطوير النموذج الأولي والتحقق من صحة الإطار في الخاتمة.

الكلمات المفتاحية: تقنية البلوكتشين، التوائم الرقمية، العقود الذكية، الميتافرس.

1. INTRODUCTION

One of the most important innovations since the integration of smart devices and the internet has been established is the possibility to constantly receive up-to-date information about an almost complete range of aspects that aff ect our lives. Flight schedules, bank transactions and product delivery are nowadays uninterruptedly tracked with precision by both customers and companies, with a view toward enhancing the quality of the experience of the final users. In this context, in which data play a paramount role in the future, the built environment is starting its transformation from a conservative static immutable entity to a more dynamic field in which information is shared between buildings and their digital twins.

While the digital model of a building has been till now primarily interpreted as a database in which to store as much information as possible, as in a classic Building Information Modelling capacity, the next step for designers as well as for contractors is to point toward the creation of a digital twin of the existing building who can inform itself with real-time data collected via sensors or other technologies able to read and communicate information such as structural performance, environmental behaviour, user interaction. Thus, data sharing affects not only the design stage but being generated from components in a real building, also the operations that occur during its whole life representing a powerful platform for planning maintenance, upgrades, and future retrofitting operations. This huge amount of data that must be created combining both those coming from the real-time database and the geometrical information of the building require at the same time to be secured from potential risks as theft and shared with all stakeholders involved in the post-occupancy maintenance in a trustful manner. The dual nature of the data, at the same time private and public, raises the necessity of adopting digital systems that allow a transparent, secure, and efficient manner of handling that data and the subsequent governance of those systems.

The combination of the physical built environment, digital twin and data encryption creates a new level of trustworthy infrastructure that shifts the way in which design and operations are planned, setting economic goals, time frames and protecting the ownership of each design decision. Within the paper, we develop a framework for integrating blockchain (BC) technologies and their crypto-economics design with digital twins (DT) within the Architecture, Engineering and Construction (AEC) Industry. We envision this Crypto-Digital Twin as the cornerstone of a blockchain-enabled shift in AEC operations, where smart contracts (SC) and crypto-economic incentives integrate and optimize the performance of the AEC industry.

2. TERMINOLOGY, MOTIVATION AND OBJECTIVES

We briefly describe terminology, then explain our motivation behind the paper and the objectives of the research.

2.1. Digital Twins

The concept of the digital twin (Information Digital Twin) was first introduced by Michael Grieves at the University of Minnesota in 2003 as the digital information equivalent of a physical product, mentioned first as a “product avatar” [Grieves 2003].

It is a digital entity representing the digital information equivalent of a physical object, set however within its environment. The DT behaves exactly as the physical product/object and can be used to simulate the behaviour and performance of the product allowing thus the possibility to predict various scenarios and then apply the best decision possible. There are certain conditions and constraints in terms of the definition and existence of the digital twin. A real-time connection between DT and physical reality might be desirable, but it is not an unquestionable requirement, as the DT might be operating without real time data. Another key feature of DTs is the fact that the DT starts existing the moment one develops the designs for the physical product/object/building, the DT exists even before the physical artefact is constructed. Within the early design stages, the digital twin currently might be called something else, for example, Building Information Model, simulation model, design or similar. This introduces another unique feature of the DTs: the twin metaphor, where the physical artefact and the DT are connected through the concepts of duality and strong similarity [Grieves 2022 speech], i.e. the DT is a digital doppelganger of the physical construct and is of course similar to the physical product, but not always identical. As such, there is a requirement, according to Grieves, that the DT exists at some point of the lifecycle of the physical construct, but there is no requirement that the DT exists prior to or after the physical construct and vice – versa. [Grieves 2022]. In fact, there have started to appear DTs where a Physical construct does not exist, for example, when one builds a DT of a supply chain. There the processes involved are the ones twined. As such, we can also anticipate that the DT can also exist after the end of the lifecycle of the construct, allowing us to use the data and insight the DT has provided in a future variation or production.

Grieves defines three stages and levels in the DT lifecycle: Prototype, Instance, and Aggregate (figure 1)

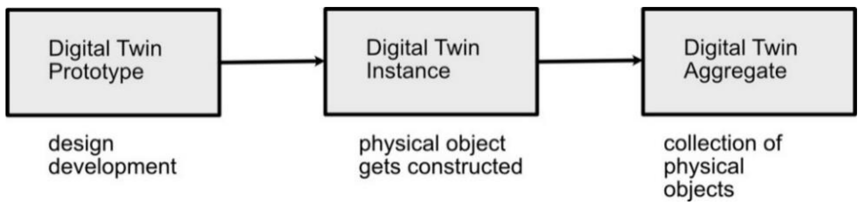

Fig.1: The Digital Twin Lifecycle, drawn by the first author.

DT prototype is the DT during design development, where the characteristics that differentiate it from any model development are those that enable the Digital Twin metaphor, and thus can be used as a litmus test on whether a prototype is destined to become or is a DT. A DT instance is the DT that corresponds to a particular physical construct, i.e. DT instance is operated at some point in tandem with the physical counterpart, while a DT aggregate is the aggregation of multiple DT instances; for example, a DT aggregate of a city has as components DT instances of buildings.

2.2. Blockchain Technologies, Smart Contracts, Tokens and DAOS

Blockchain is a distributed network of computing nodes that maintain a decentralised ledger of transactions, with an algorithmic consensus mechanism to synchronise the ledger between them. The consensus does not need a central coordinating node but emerges using a variety of algorithms, for example, proof of work, proof of stake, and proof of authority. In most public consensus blockchain algorithms, participation is incentivised in terms of good behaviour. In most cases, the blockchain designs [Buterin 2014, Nakamoto 2009], transactions are recorded on a Merkle tree, in a manner where each transaction is paired with another and the result is cryptographically hashed, with the root of the tree of transactions gets also cryptographically hashed and embedded into a block of transactions. Each block also contains the cryptographic hash of the previous block. The chain of cryptographic hashes, the distributed nature of the ledger amongst a plethora of computing nodes and the (dis)incentives encouraging the correct behaviour of nodes make the deleting or changing of information of transactions that have taken place in the past very difficult to impossible. The careful reader will note that transitions usually consist of addition and subtraction; however, one can expand the paradigm and include in transactions all programmable directions, i.e. software code. Hence, the second generation of blockchains incorporate the idea of smart contracts, i.e. the execution of software classes of code from a distributed stack machine that runs on each blockchain node in an autonomous manner, i.e. without the need for human intervention. The name smart contracts is due to the implicit guarantee that the code will be executed every time as written (Szabo 1994). Consequently, the three most important characteristics of blockchains are the concept of a trust medium, as agents and parties can record to them information without it ever being changed or deleted, the concept of incentivised participation, i.e. one gets rewarded for contributing to the common pool resources of the system, and the concept of automatic execution of code in the form of smart contracts. These ideas are then the foundation of modern cryptoeconomics, i.e., economic systems that run through blockchain code. Most economic constructs on blockchain take the form of tokens, i.e. special smart contracts that represent either some kind of uniqueness, have some utility in specific contexts, or encapsulate some value in other contexts. For example, a particular community might issue their own fungible token that is used for transactions within the community, while another might issue a non-fungible token that grants the holder governance rights over common pool resources or the organizations. In other examples, tokens might have the function of securities, i.e. they represent the ownership of an asset of value, for example, a building or a stock.

Fig.2: Ethereum Blockchain and Smart Contracts visualization from Ethviewer
Captured by first author.

Extending this idea of common pool resources, one can develop smart contracts that provide the underlying computer protocol to run an organisation, called Decentralised Autonomous Organization [Huvhenvicz thesis 2022]. It is decentralised since there is no need to ask for permission to participate and autonomous in the sense that the smart contracts operating it do not need human interaction or deliberation to execute.

2.3. Motivation, Research Question and Objectives

The research question we attempt to address is to determine the potential architecture for the use of BC in DTs in the AEC industry, i.e. in the creation of a Crypto-Twin for Buildings. Inherent within the question lies the primary interrogation of whether BC has any affinity with DTs technologies, i.e. is it really needed compared to just using trusted third parties? The motivation behind our research lies in the attempt to use BC and SC technologies to integrate, make more productive and better performing the AEC industry. Earlier work by the authors [Dounas et al 2020] has examined the use of BC to coordinate a BIM performative solution, but also on how to incentivise through collective digital design tools the creation of extremely performing architectural designs in terms of carbon, waste, building performance, only via the use of tokens and smart contracts [Dounas et al 2021]. Thus BC/SC in DTs can be used to integrate not only the DT instance of a single building but be the end point of a continuous process, where an AEC project is developed transparently from commission to design, to construction, operation, and decommissioning, via its BC enabled digital twin, with clear benefits of better security, performance, lower carbon and waste. This lies along the lines of a conceptual framework for information management via decentralised infrastructures along the entire lifecycle of a constructed asset [Jaskula et al.] and with the use of decentralised infrastructure of smart contracts and the Interplanetary Filesystem of decentralised building information modelling [Dounas 2020]. We also have observed a similar line of work by [Hunhenvicz et al.] in creating smart contracts for digital twins, in addition to further developing and prototyping the first Decentralised Autonomous Space, i.e. a cyber-physical construct that extends the Decentralised Autonomous Organisation to include the physical structure. [Hunhevicz et al., Wang et al.]. Thus, we believe that a DT based on BC and smart contracts should be one of the technical core elements of digitization in developing AEC projects, as part of an effort to develop digital factories for the AEC industry. As such the objective of this paper is to develop the conceptual paper of the BC-enabled DT, the CryptoTwin, setting a clear stage of implementation for research and industry.

3. METHODOLOGY

We have used hybrid methods in our approach to constructing the framework of the Crypto-Twin. On one side, we reviewed selected literature to determine the affinity of blockchain with the concept of the digital twins in the AEC industry and then used the results from earlier software prototype tools for blockchain in the AEC industry to develop the proposed framework for the development of Crypto-Twins [Dounas et al, 2019, 2020, 2021, Lombardi et al, 2020]. The development of this framework has followed principles of design for research [Rendel 2004] from the point of view of the AEC industry, i.e. on how to best position the prototypical framework so that its schema is general enough to be developed in multiple varied iterations by others, while in parallel we used Design Science Research methods [Peffers, K. et al., 2006] for problem identification and motivation, the determination of the objectives of the solution and the design and development of the conceptual framework. At the discussion and conclusion, we present possible avenues for the further design and development, demonstration, evaluation and communication of the impact of an artefact consisting of the Crypto-Twin model to the research community.

4. THE CRYPTO-TWIN FRAMEWORK

4.1 What is a Crypto-Twin

A Crypto-Twin (CT) is a blockchain and smart contract-enabled intelligent digital twin. This means that Crypto-twins are a sub-set of intelligent digital twins and, in many cases, will include a series of other advanced digital technologies that embody the fourth industrial revolution, such as machine learning algorithms and the Internet of Things. The distinctive characteristic though of the CryptoTwin is that the backbone of the automation of the DT is provided via smart contracts, compared to an intelligent digital twin. A second characteristic that differentiates a Crypto-Twin from an intelligent twin is the existence of collective-and-incentives-based crypto-governance. A third, not necessary but capable extension is the existence of mechanisms to operate the CT into the Metaverse [Lee et al. 2021].

4.2. Why do we need a Crypto-Twin

The main advantages that smart contracts and blockchain bring into the Digital Twin concept are the increased cybersecurity and resilience of the DT, the existence of transparent and reliable collective governance, which at the scale of DT aggregates at the level of cities is increasingly desirable, but also the interplay of crypto economics in terms of the financial incentives, resilient automation, and guaranteed execution of digital operations. While the concept of the Crypto-Twin is new, one can envisage the idea that Crypto-Twins can be used, in tandem with their physical twin, to create autonomous infrastructures, i.e. buildings and spaces that act autonomously as systems to serve their purpose. While this might be normally reserved for specialist infrastructures that need increased cybersecurity and autonomy, for example, a nuclear power plant, one can envisage the creation of CT aggregates enabling, at the level of cities or provinces, circular economies. A Crypto twin can allow a more improved integration with a circular economy via the use of tokens on smart contract and the deployment of crypto-economics frameworks for its operations.

4.3. The Proposed Crypto-Twin Structure

The framework encapsulating the Crypto-Twin contains four main components, the frontend interface, the smart contract infrastructure, the decentralized Data repository (realized on the Interplanetary Filesystem) and a simulation engine that allows us to simulate various future scenarios. In tandem, one has the physical infrastructure, i.e. the building in our case, including all energy and control systems. One might discuss whether the agents/actors and the IoT infrastructure are a part of the physical or the digital twin, but most probably, they remain a bridge between the two. (Figure 3)

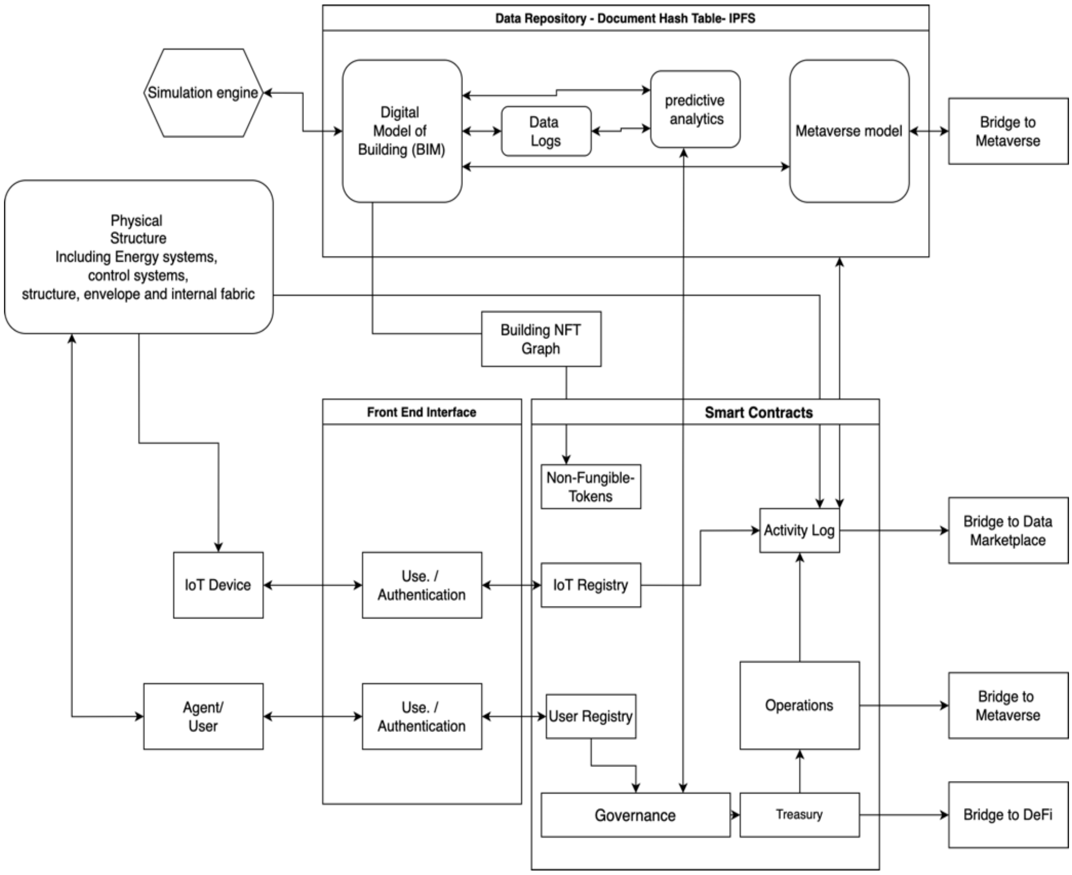

Fig.3: Crypto-Twin Framework Architecture, drawn by the First Author

The Smart contracts architecture (Figure 4) includes the following contracts: a governance smart contract, a user registry, a treasury contract, and an operations SC. On top of these, an IoT registry that authenticates IoT devices inside the SC blockchain and an activity log complete the architecture. These of course, can be more elaborate depending on the complexity of the CT needed; however, we envision that these are required as a minimum infrastructure. The governance smart contract allows the decision-making within the SC/CT environment, regulates the updates, and acts as the key contract that structures and affects how operations SC and the treasury will react: furthermore, it encapsulates how, in the end, the physical construct is governed. The treasury contract exists so that operations on the blockchain can be paid by the CT itself but also for funding any other operation for the CT and the physical construct, for example, changing window glass panels in a maintenance scenario.

The log contract, the operations SC and the treasury all have bridges, i.e. connecting scripts to the metaverse. For example, the treasury can compound interest by lending funds for a particular amount of time or borrow funds automatically via Decentralised Finance mechanisms. The activity log regulates or makes available performance data of the DT to a decentralised marketplace for buildings, where data can be exploited in aggregation: for example, all the buildings' CTs of a city could contribute their data in a CT aggregate market, in a framework that reinforces the decentralised data marketplaces concepts by Bucher and Hall [2022]. Note that to be able to address the representation of the building to the smart contract level, we use tokenization and a topology structure [Dounas et al 2021]. This allows us to create a knowledge graph of the building, where each building component is a non-fungible token, i.e. a unique digital entity that can be manipulated via the smart contracts.

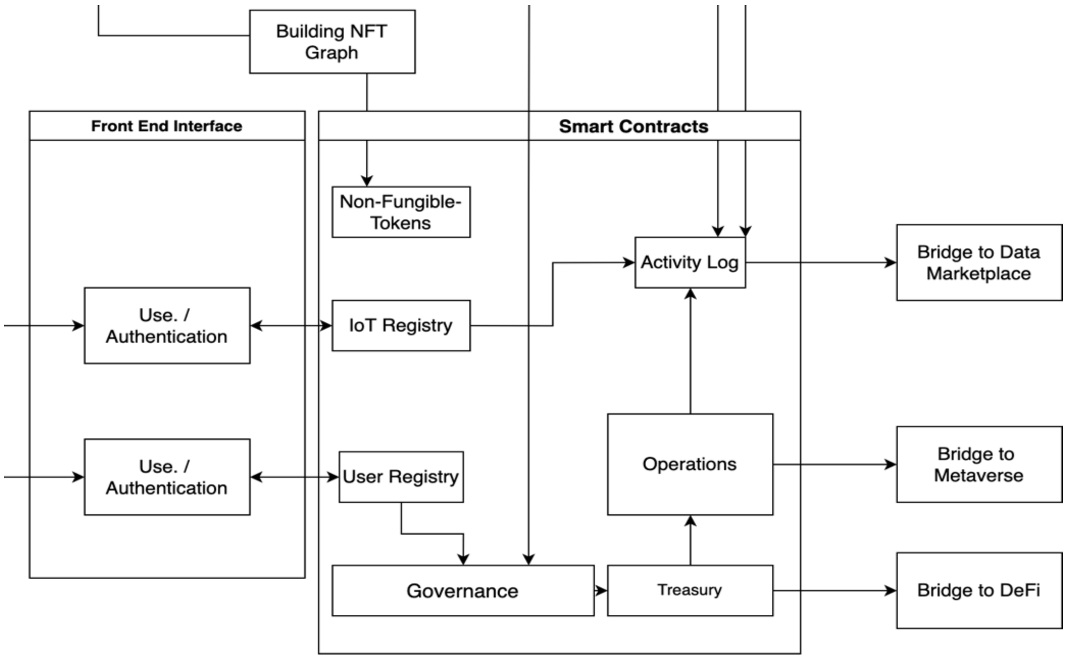

Fig.4: Crypto-Twin Smart Contract Architecture, drawn by the First Author

The main data that are not frequently updated are stored in a decentralised storage system created on the Interplanetary Filesystem (figure 5). In the case of sensitive data, those can be further encrypted, or placed behind cryptographic gateways. In that sense, the decentralized IPFS has meaning for increased resilience of the physical infrastructure hosting the data. However, this part can be replicated with various more centralised computing solutions that allow for redundancy of physical and digital infrastructure, for example, serverless architectures on a cloud. Nonetheless the important architecture here is the existence of a Building Information Model that is used as the infrastructure model twin of the physical building, its connection with a simulation and/or visualization engine that visualizes various scenarios, and of course, a data registry that contains the changes to the model. To be able to create bridges to a metaverse, a second building model is used, using geometry and modelling techniques most appropriate for the metaverse used, as BIM are very heavy and detailed in information compared to what is required in most metaverses [Decentraland, 2022]

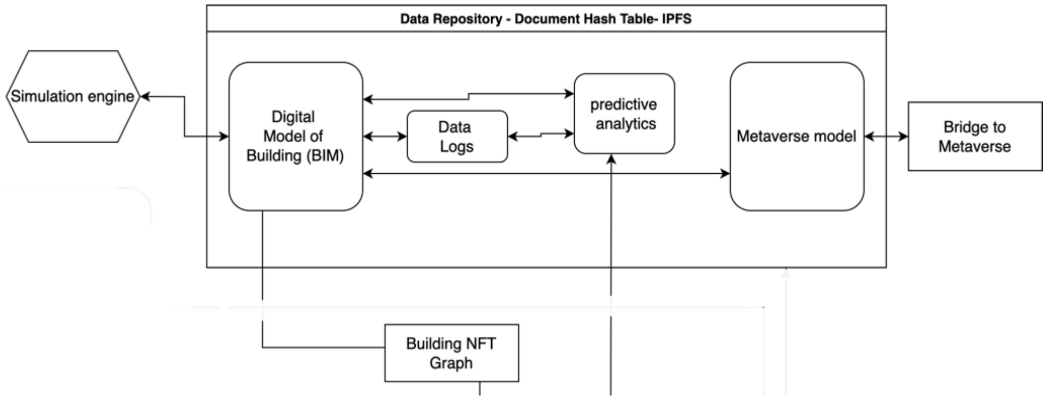

Fig.5: Crypto-Twin Decentralised Storage Architecture - Drawn by the First Author

5. DISCUSSION

The CT architecture was created by using best practices from the literature [Hunhevicz et al 2021., Li et al. 2021, Wang et al 2022., Dounas et al 2020,2021] while simultaneously creating a flexible framework that can be scaled accordingly to needs. The methods with which the framework was created follows design science research patterns, where we propose innovative artefacts to solve a problem in industry or society. In particular we employed our knowledge of the environment in which digital twins might operate in the AEc industry, fused with the knowledge base of blockchain and DT applications to design the framework and smart contract architecture. We have yet to develop a fully working prototype, as to test fully we would also need the physical artefact as well. Still, we are in the early stages of developing the SCs and the bridges of integration Further to the authors' experience with structuring SC architectures, the concepts of decentralized autonomous organizations have been used towards making the CT a key component of decentralized autonomous spaces or infrastructures. CTs carry the constraints and overhead of the technology used to implement them, i.e. blockchain and smart contracts. Additionally, certain connections with technologies that are under current development might prove problematic or not yet mature for complete integration, for example, bridges with decentralized finance or marketplaces.

6. CONCLUSION AND FURTHER DEVELOPMENT

The Crypto-Twin SC architecture and framework can readily be used in a range of cases, from traditional uses of digital twins, where we need enhanced cybersecurity, to fully decentralised, i.e. operating on-Chain Autonomous organisations that include physical infrastructure in some shape or form, such as the Decentralised Autonomous Space [Wang et al, 2022]. These formulations of DAOs, where humans, computing agents, and physical infrastructure co-exist in an autonomous organisation, challenge the orthodoxy in which we approach issues of common pool resources, governance, ownership, and co-authorship and of course design of architecture. One can certainly imagine the lifecycle of a building design - where we start with a design CT prototype that is shaped to respond to crypto-economic incentives, for example to reduce carbon impact or waste, to a CT instance that inherits and evolves the crypto-economics of the prototype, to a CT aggregate of a city, where the CTs autonomously exchange information and funds to optimise collective benefits for a city.

ACKNOWLEDGEMENTS

We would like to acknowledge extensive discussions with the members of the Architecture Decentralised Autonomous Organisation "archiDAO.io" team for inspiring part of this framework. We would like to also further acknowledge discussions with the ETH Zurich Chair of Innovative and Industrial Construction lead Prof. D.M.Hall and members of the group Dr Jens Hunhenvicz, Hongyang Wang and David Bucher for inspiration and scrutiny on the framework.

REFERENCES

- AKULENKO, E., n.d. School of Engineering Science 65.
- ALSHAMMARI, K., BEACH, T., REZGUI, Y., 2021. Cybersecurity for digital twins in the built environment: current research and future directions. Journal of Information Technology in Construction 26, 159–173. https://doi.org/10.36680/j.itcon.2021.010
- Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction - ScienceDirect [WWW Document], n.d. URL https://www.sciencedirect.com/science/article/abs/pii/S0926580521004064 (accessed 7.17.22).
- BUCHER, D. HALL, D.M. (2022) New Ways of Data Governance for Construction? Decentralized Data Marketplaces as Web3 Concept just around the Corner, Conference: The 29th EG-ICE International Workshop on Intelligent Computing in Engineering, DOI: 10.7146/aul.455.c224
- BUTERIN, V., N.D. ETHEREUM: A Next-Generation Smart Contract and Decentralized Application Platform. 36.
- CAMPOSANO, J.C., SMOLANDER, K., RUIPPO, T., 2021. Seven Metaphors to Understand Digital Twins of Built Assets. IEEE Access 9, 27167–27181. https://doi.org/10.1109/ACCESS.2021.3058009
- DENG, M., MENASSA, C.C., KAMAT, V.R., 2021b. From BIM to digital twins: a systematic review of the evolution of intelligent building representations in the AEC-FM industry. ITcon 26, 58–83. https://doi.org/10.36680/j.itcon.2021.005
- DIETZ, M., PUTZ, B., PERNUL, G., 2019. A Distributed Ledger Approach to Digital Twin Secure Data Sharing, in: Foley, S.N. (Ed.), Data and Applications Security and Privacy XXXIII, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 281–300. https://doi.org/10.1007/978-3-030-22479-0_15
- EBSCOhost | 145173003 | DIGITAL TWINNING OF THE BUILT ENVIRONMENT – AN INTERDISCIPLINARY TOPIC FOR INNOVATION IN DIDACTICS. [WWW Document], n.d.
- DOUNAS, T. JABI, W. LOMBARDI, D. (2021) ‘Non-fungible building components - using smart contracts for a circular economy in the built environment’ ‘Designing Possibilities’ Sigradi 2021, ubiquitous conference, XXV International conference of the Ibero-american society of digital Graphics.
- DOUNAS, T. LOMBARDI, D. JABI, W. (2020) ‘Framework for Decentralised Architectural Design:BIM and Blockchain Integration’, International Journal of Architectural Computing, Special issue eCAADe+SiGraDi “Architecture in the 4th Industrial Revolution.” https://doi.org/10.1177/1478077120963376
- DOUNAS, T. LOMBARDI, D. (2019) ‘Blockchain Grammars’ in ‘Intelligent and informed’ CAADRIA 2019, Wellington, New Zealand
- GRIEVES, M., 2021. Excerpt from Forthcoming Paper Intelligent Digital Twins and the Development and Management of Complex Systems The “Digital Twin Exists ONLY After There Is A Physical Product” Fallacy.
- GRIEVES, M., VICKERS, J., 2017. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. pp. 85–113. https://doi.org/10.1007/978-3-319-38756-7_4
- HUNHEVICZ, J.J., MOTIE, M., Hall, D.M., 2022. Digital building twins and blockchain for performance-based (smart) contracts. Automation in Construction 133, 103981. https://doi.org/10.1016/j.autcon.2021.103981
- Intelligent digital twins and the development and ... | Digital Twin [WWW Document], n.d. URL https://digitaltwin1.org/articles/2-8 (accessed 6.23.22).
- HUNHEVICZ, J., WANG, H., HESS, L. HALL, D., 2021.no1s1 - a blockchain-based DAO prototype for autonomous space [WWW Document], n.d. URL https://ec-3.org/publications/conference/paper/?id=EC32021_185 (accessed 7.14.22).

- JASKULA, K., PAPADONIKOLAKI, E., ROVAS, D., 2022. Conceptual framework for decentralised information management along the entire lifecycle of a built asset., in: Computing in Construction. Presented at the EC3 Conference 2022, University of Turin, pp. 0–0. https://doi.org/10.35490/EC3.2022.168
- KARPISTSENKO, A., 2016. Networked Intelligence: Towards Autonomous Cyber Physical Systems.
- KOR, M., YITMEN, I., ALIZADEHSALEHI, S., 2022. An investigation for integration of deep learning and digital twins towards Construction 4.0. Smart and Sustainable Built Environment ahead-of-print. https://doi.org/10.1108/SASBE-08-2021-0148
- LEE, L.-H., BRAUD, T., ZHOU, P., WANG, L., XU, D., LIN, Z., KUMAR, A., BERMEJO, C., HUI, P., 2021. All One Needs to Know about Metaverse: A Complete Survey on Technological Singularity, Virtual Ecosystem, and Research Agenda. https://doi.org/10.48550/arXiv.2110.05352
- LOMBARDI, D. DOUNAS, T. CHEUNG, L. H. JABI, W. (2020). Blockchain for Validating the Design Process. In SIGraDI 2020. Medellin.
- LU, Q., CHEN, L., LI, S., PITT, M., 2020. Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. Automation in Construction 115, 103183. https://doi.org/10.1016/j.autcon.2020.103183
- MOHAMED, A., SHAFIQ, M., SAMI UR REHMAN, M., 2021. Applications of Digital Twins for Asset Management in AEC/FM Industry - A Literature Review.
- NAKAMOTO, S., n.d. Bitcoin: A Peer-to-Peer Electronic Cash System 9.
- OPOKU, D.-G.J., PERERA, S., OSEI-KYEI, R., RASHIDI, M., 2021. Digital twin application in the construction industry: A literature review. Journal of Building Engineering 40, 102726. https://doi.org/10.1016/j.jobe.2021.102726
- (PDF) no1s1 - a blockchain-based DAO prototype for autonomous space [WWW Document], n.d. URL https://www.researchgate.net/publication/353515227_no1s1_-_a_blockchain-based_DAO_prototype_for_autonomous_space (accessed 7.14.22).
- PUTZ, B., DIETZ, M., EMPL, P., PERNUL, G., 2021. EtherTwin: Blockchain-based Secure Digital Twin Information Management. Information Processing & Management 58, 102425. https://doi.org/10.1016/j.ipm.2020.102425
- RENDELL, J., 2004. Architectural research and disciplinarity. Architectural Research Quarterly 8, 141–147. https://doi.org/10.1017/S135913550400017X
- ROXIN, A., ABDOU, W., GINHAC, D., DERIGENT, W., DRAGOMIRESCU, D., MONTEGUT, L., 2019. Digital Building Twins - Contributions of the ANR McBIM Project, in: 2019 15th International Conference on Signal-Image Technology & Internet-Based Systems (SITIS). Presented at the 2019 15th International Conference on Signal-Image Technology & Internet-Based Systems (SITIS), pp. 404–410. https://doi.org/10.1109/SITIS.2019.00071
- TAN, C., LI, X., LUAN, T.H., GU, B., QU, Y., GAO, L., 2021. Digital Twin Based Remote Resource Sharing in Internet of Vehicles using Consortium Blockchain, in: 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall). Presented at the 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), pp. 1–6. https://doi.org/10.1109/VTC2021-Fall52928.2021.9625367
- YITMEN, I. AND ALIZADEHSALEHI, S., 2021. Towards a Digital Twin-based Smart Built Environment, 2021. BIM-enabled Cognitive Computing for Smart Built Environment. CRC Press. https://doi.org/10.1201/9781003017547-2
- VOM BROCKE, J., HEVNER, A., MAEDCHE, A., 2020. Introduction to Design Science Research, in: vom Brocke, J., Hevner, A., Maedche, A. (Eds.), Design Science Research. Cases, Progress in IS. Springer International Publishing, Cham, pp. 1–13. https://doi.org/10.1007/978-3-030-46781-4_1
- WANG, H., HUNHEVICZ, J., HALL, D., 2022. What if properties are owned by no one or everyone? foundation of blockchain enabled engineered ownership, in: Computing in

Construction. Presented at the EC3 Conference 2022, pp. 0–0. https://doi.org/10.35490/EC3.2022.213

- WU, Y., ZHANG, K., ZHANG, Y., 2021. Digital Twin Networks: A Survey. IEEE Internet of Things Journal 8, 13789–13804. https://doi.org/10.1109/JIOT.2021.3079510