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Digital Twins and Blockchain – Proof of Concept

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Abstract

Digital Twins and Blockchain are key elements that when connected allow continuous data acquisition in the factory. As the connection between digital twins and blockchain is rather under-explored, the key contribution of this paper is the conceptual development of a digital twin prototype connected with an Ethereum-based blockchain. The outcome of the paper provides a concept to ensure the unique tokens represent the physical assets without being tampered with by applying digital twin technology. The paper includes a case study focused on Matrix-Structured Manufacturing Systems for Small and Medium-sized Enterprises.

Keywords: Digital Twins; Blockchain; Distributed Ledger Technology; Matrix-Structured Manufacturing System; Token

1. Introduction

Over the recent years, Industry 4.0 enabling technologies have increased in popularity, not only in academia but also in the industry. This fourth industrial revolution brings several benefits and optimizations through technologies such as digital twins (DT), and Internet-of-Things (IoT) that are based on a solid data foundation. With these technologies, more crucial data becomes available in the supply chain, and especially small and medium-sized enterprises (SMEs) face the challenge of trusting external parties with their intellectual property rights (IPR). Blockchain technology enables data storage in an immutable and decentralized way, ideally suited for traceability in manufacturing processes, thus increasing the trust throughout the supply chain. This is achieved through, for instance, ERC721 tokens on the Ethereum platform that is a non-fungible token [1]. This results in unique tokens representing each product being produced. With smart contracts, it is furthermore possible to create conditions to be met, before a transfer can be performed. In this way, payment is not only automated but also optimized, as payment reductions can be programmed in case not all conditions of a contract have been fulfilled. Naturally, both stakeholders involved in the smart contract need to reach an agreement before it is valid.

When SMEs are moving from the prototyping phase to the production phase, several stakeholders are typically introduced to assist in the process, for example in Design for Manufacturing. The agreements between the stakeholders are often based on trust, posing a risk that the IPR is violated. As this can happen in multiple stages, the need for a transparent and immutable technology is present. When connecting the digital twin with the blockchain, it is possible to measure eventual tampering with the product during the production thus indicating if the IPR is violated.

The key contribution of this paper is the conceptual development of a digital twin connected with an Ethereum-based blockchain, thus ensuring ERC721 tokens represent the physical assets without being tampered with. In this way, the paper aims to bridge the research gap between digital twins and blockchain.

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The paper is structured in six sections, where section 2 identifies the relevant literature within DT and Blockchain technology. Section 3 describes the concept, including the conceptual development of the digital twin, the blockchain, and the connection. Section 4 describes the case study. In section 5 the results are discussed, and future work proposed. Section 6 concludes the paper.

2. Related work

This section identifies relevant literature on both digital twins and blockchain technology addressing the current research gap between these fields.

Distributed Ledger Technology (DLT) such as blockchains have sparked a lot of interest, primarily due to Bitcoin and Ether, where such cryptocurrencies, in general, are the most popular use cases [2]. However, early adopters have set about applying blockchain beyond financial markets rather than focusing on different parts of the supply chain to enhance transparency and trustworthiness [3]. Some current applications are seen in shipping, fishing industry, pharmaceuticals, rough-cut diamonds, insurance, coffee and more [4]. With the smart contracts in Ethereum, it has been possible to run complex scripts that allow the development of tokens, such as ERC20 and ERC721 tokens [5–7]. These tokens furthermore enable the use of blockchain in supply chains [1].

Digital Twins, originally proposed by Dr. Grieves and Vickers [8], are often defined in various ways, typically depending on supplier and application area [9]. Based on the definition by Boschert and Rosen [10], a digital twin is “a linked collection of only the relevant data and models. The models that make up the digital twin are specifically designed for their intended purpose.” This will serve as the foundation of a digital twin described in this paper.

Previous work has been performed to combine digital twins and blockchain through tokenization. Weingärtner [6] describes how IoT devices will serve as the foundation for connecting the physical asset and the digital replica. However, the ERC721 token is though not applied. The ERC721 will be applied in the case study, as it is non-fungible. This means that each product is regarded as a unique token, thus Heber and Groll [11] also present a paper that describes how a digital twin and blockchain can be integrated, this time in the automobile industry to increase traceability in the supply chain.

It is possible to deduce that current work has already been thoroughly done within both digital twins and blockchain. Limited research has though been performed in the connection between these two fields. Mandolla et al. describes the connection at supply chain level [12], where Huang et al. describes a blockchain-based data management approach of the products digital twin [13].

A gap in research is therefore present, as unique tokens have not been connected through digital twins, with the physical asset, therefore the individual product cannot be tracked and distinguished in the factory. The gap furthermore consists of the digital twin and Blockchain being integrated at the manufacturing system level, compared to previous work focusing on supply chain and product level.

3. Concept

This section will focus on the conceptual solution to connect an ERC721 token with a digital twin. The solution consists of three layers as seen in Fig. 1: a physical layer, a connection layer, where the ERC721 token and digital twin interact, and a blockchain layer. The key focus of the paper is centered around the communication layer that ensures the non-fungible token represents the physical asset through data from an immutable digital twin.

The physical layer represents the processes or production equipment that is producing the product. In general, all processes and machines that can be digitized through a digital twin can be used in this step. Alternatively, the quality inspection process can be applied, assuming it can be digitized, as it provides the relevant data though only in one instance, and not throughout the whole process.

With the introduction of a digital twin, the product is also digitally represented. The digital twin is therefore in the connection layer, between the physical and digital layers. So is the token that in blockchain represents the physical asset or product. By connecting the data from the digital twin and the token, it will be possible to transfer physical events to the blockchain. As the token can be enriched with data from the digital twin, it is possible to create smart contracts based on the conditions, the physical representation experience. These smart contracts can contain conditions, based on tolerance intervals, rework, manufacturing time, etc. depending on the product. The communication layer, therefore, translates the physical processes, through a digital twin, to the ERC721 token, representing the product, that is used to evaluate the parameters in a smart contract thus determining aspects like the future material flow.

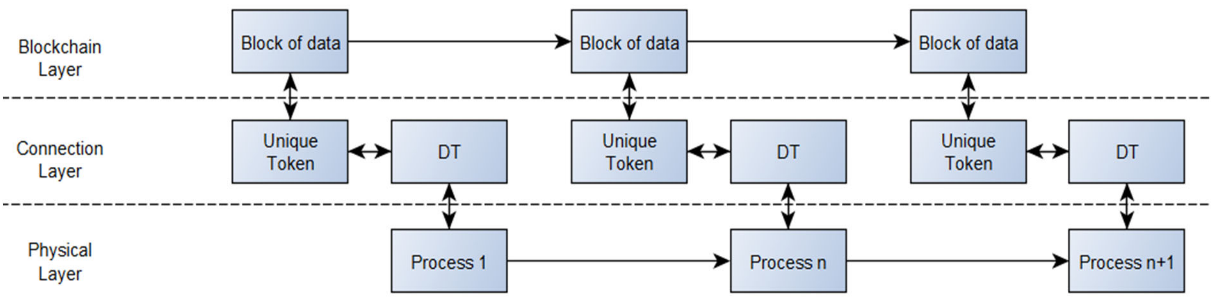

Fig. 1 Conceptual Digital Twin and Blockchain integration

As seen in Fig. 1, two major components need to be developed: the digital twin and the blockchain. Furthermore, the interface between the digital representation and the token needs to be designed. The blockchain will be designed initially, as the digital twin should be adaptable to different blockchain solutions, depending on the application. The data from the digital twin should be easily accessible, though only the relevant data from the smart contract will be applied.

The blockchain design is based on the decision path presented by Pedersen, Risius, and Beck [14]. In this context, the public verifiability and transparency are limited to stakeholders around specific cases. But it is scalable that new stakeholders can be added to the process. Applying the model yields that a private blockchain is suitable in most cases. In cases where for example the trust is strong between the participants, the decision-path suggests that a blockchain solution is not needed. Afterward, a consensus algorithm needs to be applied, to verify the correct addition of blocks to the chain. For this, the Proof-of-Authority will be applied, as it is crucial to reveal the identity to the stakeholders in the supply chain [15]. In this way, tampering can be limited, as a bad reputation leads to exclusion of the blockchain. This is applied to the individual steps in the processing of a product. It means for example that a machine can be excluded, in practice meaning calibration or repair, as it provides false data. This consensus algorithm furthermore implies a permissioned blockchain, where the different machines or humans need to be invited to the mining pool, to add blocks to the chain. Based on the consensus algorithm and the private blockchain, the trust is kept within the private network and further enhanced, as the cost of mining a block is revealing the identity. This ensures transparency and increases trust, although at the cost of privacy. Immutability is to a certain degree ensured, as 51% attacks will only occur in case equipment tolerances and human errors are yielding the same results. Finally, the need for more complex smart contracts exists, where this is achieved on the Ethereum platform, with non-fungible ERC721 tokens.

The ERC721 tokens are applied in this conceptual model as they provide several benefits for this concept. ERC721 tokens are typically used for collectibles, such as in the blockchain-based game CryptoKitties [5], where each token is unique thus non-fungible. In this way, it is possible to associate a unique token with a unique product. This is not possible with token standards such as ERC-20.

The DT is initially designed digitally to optimize the communication design with the ERC721 token. This is further supported by the typical approach of computer-aided design, where the digital part is created initially, and the physical part is created from the digital representation. Through IoT connection, the communication between the physical and digital representation of the DT is realized. Depending on the product, this communication can yield interaction both ways, meaning a change in the digital representation will influence the physical representation and vice versa. This is mostly relevant for manufacturing systems, although other application areas can benefit from this. In this way, smart contracts can also influence the machine settings, ensuring flexibility and adaptability.

The smart contracts in the blockchain allow automatic material flow decisions in the manufacturing system, as the parameter deviation intervals are agreed before initializing production. This can be done internally in the organization, or through external specialists, depending on the company case. This means that the DT provides the data foundation for evaluating the smart contract parameters, and if all parameters are within agreed deviations, the product can continue the material flow path, alternatively, rework needs to be done. This is automatically occurring thus it requires an adaptable manufacturing system that can account for this.

The developed concept will be verified in the following section through a case study of a start-up company.

4. Case Study

We interviewed the founders of a start-up company and followed up closely the entire innovation process [16] from the early phase ideation until they launched the first product in the market in 2017. During the product development process, the core team needed to involve external partners to fill their knowledge gaps. They need to consult structural engineering professionals to finalize the prototype and make it ready for manufacturing [17]. Afterward, they still needed to go through several iterations of changing the product design in collaboration with the engineers at the factory located in another country. The collaboration was based on contract and trust. On one hand, they have to share the product design documents with third parties openly. On the other hand, the factory needed to explain to them the details of the manufacturing process.

Many small and medium-sized companies follow similar product development and production process, i.e. develop the core technology in the firm, may involve external experts in the design phase, and outsource the manufacturing and production to other companies, often in other countries. To protect the rights of each party, only based on a contract does not always work. Therefore, we suggest a concept of a matrix-structured manufacturing system that could serve multiple SMEs.

The case study focuses only on the start-up company, although the principles behind can be replicated without influencing the concept of an MMS. Initially, the start-up company and the Design for Manufacturing experts will share information through a private blockchain to exchange confidential information on the MMS processes as well as the technical drawings from the company. This leads to specifying process parameter intervals such as tolerance deviations, deviations in processing time, and similar on the product in the given process. This information serves as the foundation for comparison in a smart contract.

In this case study, injection molding, CNC milling, and assembly will serve as examples of processes the product will go through in the MMS. The parameters and deviation intervals, based on rough estimations, can be seen in Table 1. Furthermore, the material flow is defined, as it can be seen in Fig. 2. The circled numbers represent different processes that the cell can perform.

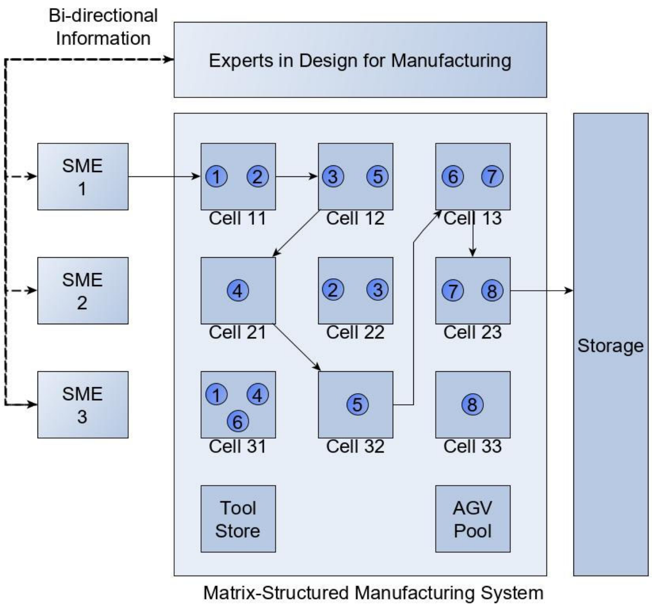

Fig. 2 Matrix-Structured Manufacturing System applied on Case Study

Table 1. Smart Contract Specifications

Number	Process	Parameter	Deviation Interval
1	Injection Molding	Tolerance	±0.05mm
		Processing Time	± 5 minutes
2	CNC Milling	Tolerance	±0.1mm
		Processing Time	± 3 minutes
8	Assembly	Sensor reading	± 0.02 V

Initially, the digital twin of the molding machine will update the ERC721 token, representing the product, with the processing time and the product dimensions. Upon finished operation, the smart contract requirements are evaluated. If the parameters are within the given intervals, the product can continue to the next process, as seen in Fig. 3., alternatively it will need rework. This additional process step will also be documented in the blockchain, although this is not covered in Fig. 3. The same approach follows for the CNC milling, and further processes until the assembly process is reached. As this is the final processing step, the final block is added to the blockchain. Afterward, the product goes to storage and then shipment, though no digital twin is developed of these processes.

5. Discussion

By applying the developed concept on the case study and comparing it to the start-up company case, several differences can be highlighted. First of all, by applying the developed concept, the start-up company can protect the IPR by only allowing the strictly necessary information on the product to be accessed by the manufacturing system. Depending on the confidentiality, it can reveal all, some, or no parameters. Processing information can be included in the blockchain for fully autonomous processes, thus the start-up company would be in full control of the information.

Secondly, the start-up company gets information on product status after each process has finished. This is done through smart contracts, where the parameters are evaluated during each process, and the material flow is determined hereafter. This not only maximizes the quality of the product for the start-up company but also allows the manufacturing system owner to optimize machine or process performance through continuous data collection.

Furthermore, the different stakeholders can trust each other and the data that is shared between them. This means that for example the need for contracts that are approved by lawyers is no longer necessary.

The proposed concept shows several benefits, although only certain contexts experience maximized benefits. This is especially in manufacturing systems that are highly digitized and where process data is easily available. The manufacturing system furthermore needs a suitable IT infrastructure to support the data flow.

For the adaptable manufacturing company, it enables multiple SMEs to have parts produced independently without managing vast amounts of confidential data, thus not only minimizing the administrative work related to contracts but also improving trust and transparency in the production. Rigid manufacturing systems will not achieve the same level of benefits by implementing the concept, although the value can still be created.

The proposed concept does though also have some limitations, especially in low mix high volume manufacturing systems. In this case, the MES/ERP integration provides

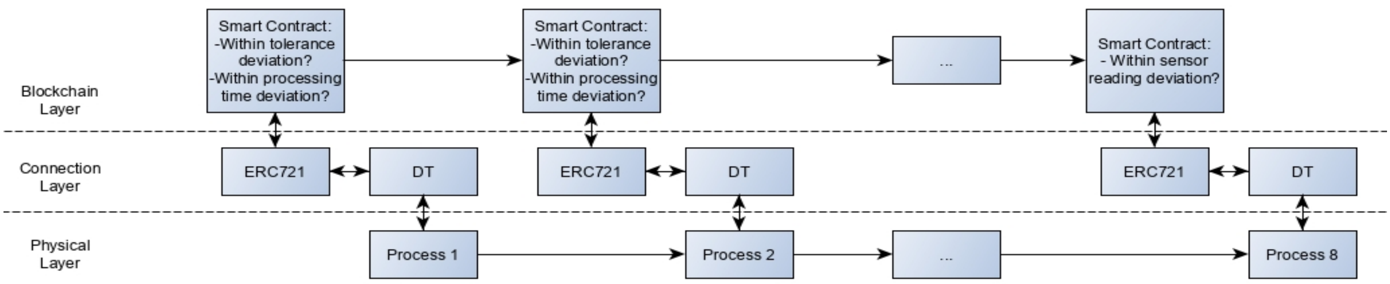

Fig. 3. Developed concept applied on case study

greater benefits than the proposed concept. This is due to the infrastructure needed to support multiple blockchains. In cases where for example injection molding processes produce millions of parts daily, a blockchain and token for each part result in less ideal results compared to MES/ERP solutions, designed for high volume production.

Furthermore, in multinational enterprises that design and manufacture the products internally, the design and manufacturing departments can communicate directly and share confidential data freely. The trust is therefore high resulting in no need for a blockchain solution, as the PDM system provides similar benefits.

6. Conclusion

This paper presents a conceptual integration between digital twins and Ethereum based blockchains through the ERC721 token. The concept shows several benefits compared to current solutions. This includes transparency on how Intellectual Property Rights are treated in the manufacturing stage. Additionally, smart contracts can be developed, enabling optimized and automized material flow throughout the manufacturing system on individual products.

Future works of this study will be targeted on developing a prototype, partly on the blockchain, partly on the digital twin. The connection layer will also be further investigated through a prototype. Future works will also investigate how the concept can be applied to other reconfigurable manufacturing systems. Finally, the current concept primarily covers a digital twin and therefore the blockchain of the processes thus leaving out the digital twin of the product and therefore also the blockchain hereof. Future studies will also investigate the interaction between the two blockchains by applying principles from for example the Polkadot project [18]. In addition to the previous future works, it will also be investigated how blockchain-related topics such as redundancy, scaling, and immutability influence the concept. Finally, other technologies instead of blockchain will be investigated, such as Directed Acyclic Graphs, to address issues with the redundancy, scaling, and immutability, but also complexity and cost. Other token standards, such as ERC-1155 will be further researched to investigate implementation in the concept.

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