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A teaching concept to convey benefits of blockchain-based applications in supply chains and production by means of learning factories

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Abstract

Blockchain is a technology for the secure processing and verification of data transactions based on a distributed peer-to-peer network that uses cryptographic processes, consensus algorithms, and backward-linked blocks to make transactions virtually immutable. Within supply chain management, blockchain technology offer potentials in increasing supply chain transparency, visibility, automation, and efficiency. However, its complexity requires future employees to have comprehensive knowledge regarding the functionality of blockchain-based applications in order to be able to apply their benefits to scenarios in supply chain and production. Learning factories represent a suitable environment allowing learners to experience new technologies and to apply them to virtual and physical processes throughout value chains. This paper presents a concept to practically transfer knowledge about the technical functionality of blockchain technology to future engineers and software developers working within supply chains and production operations to sensitize them regarding the advantages of decentralized applications. First, the concept proposes methods to playfully convey immutable backward-linked blocks and the embedment of blockchain smart contracts. Subsequently, the students use this knowledge to develop blockchain-based application scenarios by means of an exemplary product in a learning factory environment. Finally, the developed solutions are implemented with the help of a prototypical decentralized application, which enables a holistic mapping of supply chain events.

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Keywords: Blockchain; Decentralized Applications; Teaching Concept; Learning Factories

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1. Introduction and rationale of the paper

In 2008, the pseudonym Satoshi Nakamoto published the Bitcoin white paper and thus introduced the blockchain technology with the aim of changing the traditional financial sector by making trusted third parties superfluous [1]. Blockchain technology allows the processing and verification of data transactions based on a distributed peer-to-peer network. It uses cryptographic procedures, consensus algorithms, and back-linked blocks to make transactions practically unchangeable [2]. In 2013, Vitalik Buterin introduced Ethereum and extended the financial aspects of Bitcoin by embedding a fully-fledged Turing-complete programming language [3]. A Turing-complete language design enables complex constructs such as loops and conditions, which allows the creation of general-purpose programs [4]. The establishment of the Ethereum blockchain with its Turing-complete programming language thus represents the birth of blockchain-based 'smart contracts' and decentralized applications beyond the financial sector [3]. Due to this new variety of decentralized applications, blockchain technology has increasingly become the focus of Industry4.0-driven projects [5]. Here, blockchain's main

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emphasis is still on applications in the financial sector, directly followed by manufacturing data protection and the identification of products and assemblies [6]. In particular in supply chain management, the immutable, decentralized, and secure characteristics of blockchain technology represent important properties to increase transparency, automation, visibility, and disintermediation in Industry4.0 supply chains [7].

For Dobrovnik et al. [8], the complexity of blockchain technology represents a main obstacle to overcome when adopting blockchain technology in industry. This can lead to scenarios where companies create their own blockchain platforms specifically designed to meet the needs of their individual application scenario without ensuring interoperability of the application [8]. Furthermore, the complexity of blockchain technology itself still impacts a convenient and efficient programming when developing complex, secure, and reliable decentralized applications [9]. These complex characteristics require industry-oriented test and development environments giving young engineers access to emerging technologies in order to facilitate the simulation in the design and operation of novel manufacturing systems [10]. Furthermore, the versatile concepts incorporated by blockchain technology (such as hashing, distributed ledgers, or consensus algorithms) make an understanding of this technology beneficial for students from all disciplines of engineering [11]. Therefore, Mourtzis et al. [12] published a first paradigm focusing on blockchain technology in higher research organizations by means of learning factories. The proposed framework represents an important foundation for educating young engineers and sharing intellectual property with industrial organizations. However, the approach by Mourtzis et al. [12] mainly focuses on the complexity regarding the establishment of a blockchain infrastructure and summarizes first ideas regarding token-based reward systems at higher research institutions. This paper extends the approach of Mourtzis et al. [12] focusing particularly on a teaching concept for decentralized applications in supply chain management and production. While the approach by Mourtzis et al. [12] is essentially limited to applications in the higher research domain, the concept in this paper aims at integrating industrial application scenarios into a teaching concept by means of learning factories. For this purpose, this paper adapts the infrastructural design based on the Ethereum blockchain by Mourtzis et al. [12] and deploys on it a smart contract application for mapping asset-related supply chain events.

In the next chapter, this paper presents a teaching concept consisting of two stages to practically transfer blockchain knowledge to future engineers and software developers working within supply chains and production operations in order to sensitize them regarding the advantages of decentralized applications. Here, learning factories represent an important environment when developing and testing new prototypical industrial applications.

2. Blockchain teaching concept by means of learning factories

The proposed teaching concept consists of two stages. The first stage aims at generating a common understanding of blockchain-based decentralized applications. In the second stage, the knowledge is practically applied to production processes and supply chain events by mapping them in a prototypical application.

2.1. Workshop to generate understanding of decentralized applications

The first part of the workshop involves the teaching of general blockchain-specific procedures in a peer-to-peer network. This includes block structures of backward-linked blocks, transaction processing, hashing, and the functionality of consensus algorithms. The concept is based on the functionality of the Bitcoin network, including the Proof-of-Work consensus algorithms as described by Satoshi Nakamoto [1]. After understanding the basic functionality of blockchain technology and cryptocurrencies, the second part of the workshop extends the operating modes with a simple smart contract. This smart contract aims at sensitizing the participants towards the tokenization of assets, which represent a key principle when adopting decentralized applications in the industry [13].

For the workshop, all participants are divided into groups. Each group represents a node in the blockchain peer-to-peer network. Subsequently, each group receives blank posters representing the initially empty blocks of the blockchain. Finally, ‘Play Coins’ are allocated to the groups, which represent the currency throughout the workshop. The game procedure with its four main phases is summarized in Figure 1. Here it should be noted that the listed number of groups, block size, and initial balance can be flexibly adjusted depending on the group size and objectives. The values given only serve as examples. The workshop was originally designed as in-person training inside the learning factory environment. However, due to the COVID-19 pandemic, the structure of the workshop also allows an adaption to an online format according to the hybrid teaching model in learning factories by Mourtzis et al. [14].

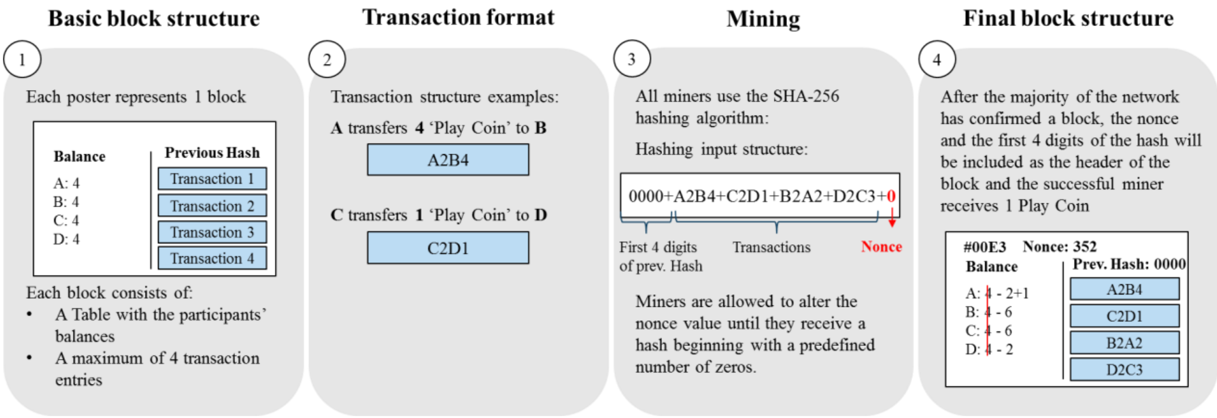

Fig. 2. Basic workshop procedure.

Basic block structure. Each block contains a balance table and the respective data entries. According to the blockchain structure introduced by Satoshi Nakamoto [1] each block must contain the hash of the previous block. To simplify this procedure for the workshop participants, the first four digits of the typically 64 digit long hash value is sufficient. Additionally, each block can only contain a predefined number of transactions. This allows the limited block size of current blockchain platforms to be simulated in the course of the workshop [15].

Transaction format. The transaction format defines a common format for all transactions to be processed in the peer-to-peer network. All transactions need to be in exactly the same format in order to ensure a network consensus at a later stage. In this example, A2B4 translates to 'Group A transferring 4 Play Coins to Group B'. The transactions of each group can be written down on paper slips and must be duplicated depending on the total number of groups. Subsequently, each group hands over its transactions to the other groups. Such procedure simulates the information broadcast of transactions in the Bitcoin peer-to-peer network whereas one peer typically connects to eight outbound connections [16].

Mining. The mining involves a procedure reflecting the Proof-of-Work consensus algorithm. Therefore, all groups access a hashing algorithm, preferably the SHA-265 hash function used in the Bitcoin protocol [1]. The SHA-256, and a hash function in general, is "a function that maps bit string of arbitrary length to a fixed-length bit string" [17]. Compared to other hashing algorithms, the SHA-256 has the advantage to result in a clear hexadecimal number, which facilitates comparison among participants. Step 3 in Figure 1 shows the exemplary format of the input. Thereby, the nonce represents the only variable allowed to be altered by the nodes. Each node alters the nonce value trying to find a hash matching the predefined difficulty of the network. If the nonce value is altered manually, a difficulty of hash values starting with two zeros is recommended. It is important to create an artificial delay in block creation so that all groups have sufficient time to distribute and arrange their transactions. The first group finding a valid hash proposes its potential new block to the network.

Final block structure. The proposal of a potential new block interrupts the mining process of all other nodes. The other participants recreate the transaction order of the proposed block and validate the proposed nonce value. If the majority of the network confirms the validity of the block, the first 4 digits of the respective hash will be included as the header of the block. The group that proposed the block receives one Play Coin as a reward. After this, all groups start with a new empty block, take over the new balance and the hash of the previous block, and the procedure repeats.

Once the functionality of cryptocurrencies has been internalised by all participants, a smart contract component is added to the procedure. This extension impacts the block structure as well as the transaction format. The extended procedure is shown in Figure 2.

Extended block structure. The extended block structure includes the element of a basic smart contract by extending the balance reflected in each block with an additional smart contract table. Similar to smart contracts on the Ethereum blockchain, the smart contract consists of a smart contract address and a basic function, which – in this workshop – allows participants to add unique names to the smart contract. This extended block structure allows to playfully explain the functionality and differences between fungible tokens and non-fungible tokens (NFTs).

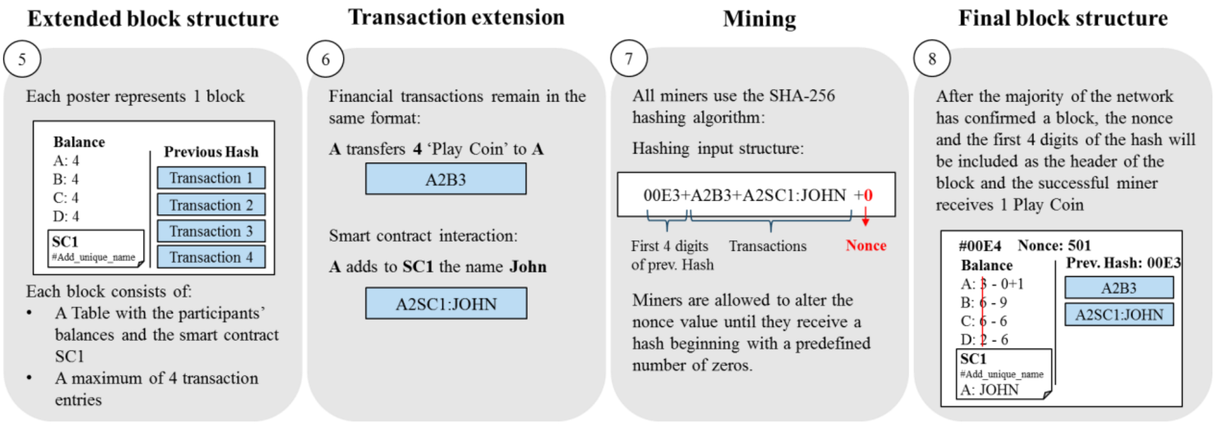

Fig. 2. Extended workshop procedure.

Extended transaction format. To allow the participants to interact with the smart contract, an additional transaction format is necessary. Besides the currency transactions, new smart contract transactions are added allowing to trigger the smart contract function and to add names to the smart contract. As shown in Figure 2, A2SC1:JOHN translates to 'Group A adds the name John to the smart contract with the address SC1'. This enables the simulation of a transaction-based smart contract interaction as used on the Ethereum blockchain [18].

The mining and the final block structure work similar to the basic procedure. However, the new smart contract element allows a parallel processing of financial transactions and non-financial smart contract interactions. Like this, blockchain-specific problems such as the double-spending problem and blockchain forks can be simulated and understood in a playful way. Based on the manifestation of the blockchain-specific processes, the next stage of the teaching concept puts the knowledge into practice by means of a prototypical smart contract-based application

2.2. Prototypical application to holistically map supply chain events

The prototypical application adopts 'smart NFTs' to enable a blockchain-based ecosystem allowing to holistically map complex products in dynamic supply chains. Arcenegui et al. [19] describe 'smart NFTs' as NFTs used for complex applications that require an extension of the minimum specifications defined in token standards with further attributes and functions. In this context, the term 'holistical mapping' refers to the mapping of the core supply chain events, object creation/removal, object transformation, object aggregation/disaggregation, and object transactions [20]. This allows study groups to work out application scenarios and transfer them to products in the learning factory. The application consists of an authority concept as well as a smart NFT concept. The smart contract uses the Turing-complete Solidity programing language and runs on a private Ganache Ethereum network together with a ReactJS user interface.

The prototypical application is based on a central authority principle. The deployer of the smart contract automatically becomes the application's administrator with the ability to add addresses (public keys) of supply chain partners to be involved in the application. Added partners are then part of the supply chain ecosystem and can receive, create, and send tokens. This enables the mapping of authoritative structures in dynamically changing supply chains.

The smart NFT concept includes the establishment of 'token blueprints' that represent the manufacturing process. A token blueprint can be seen as a function within a smart contract that defines a token's structure and its requirements to be met when minting it. Each blueprint consists of a unique identifier (token blueprint ID) and a token structure definition. To ensure the uniqueness of each token blueprint, the token blueprint ID is generated by hashing the content of the token structure definition. Therefore, the token blueprint ID is a logical result of its content. Additionally, each blueprint is connected to an owner, which refers to the blockchain account address having permission to mint tokens with the blueprint.

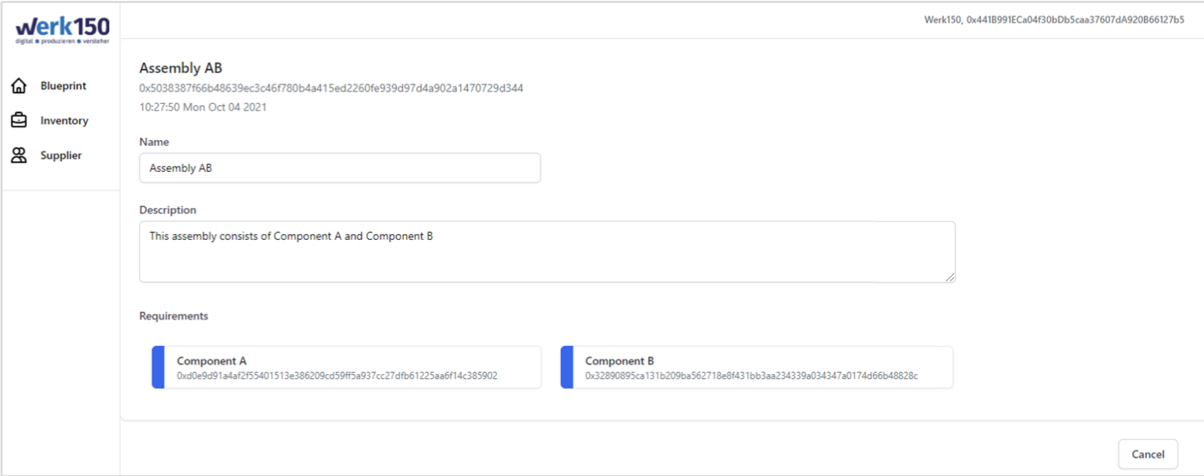

Fig. 3. Blueprint of an assembly consisting of two components.

After the successful creation of a token blueprint, the blueprint function allows all authorized suppliers to add tokens minted by existing blueprints to the requirements of subsequent token blueprints. Figure 3 illustrates this situation by means of the user interface. For exemplary purposes, the application represents a token blueprint for the ‘Assembly AB’, which consists of ‘Component A’ and ‘Component B’. The creation requirements ensure that the creator of ‘Assembly AB’ owns both a token minted with a token blueprint for ‘Component A’ and ‘Component B’. As long as these conditions can be met, the owner of the blueprint for ‘Assembly AB’ can create any number of tokens of the same type with identical technical properties, which are, however, clearly identifiable by their unique IDs.

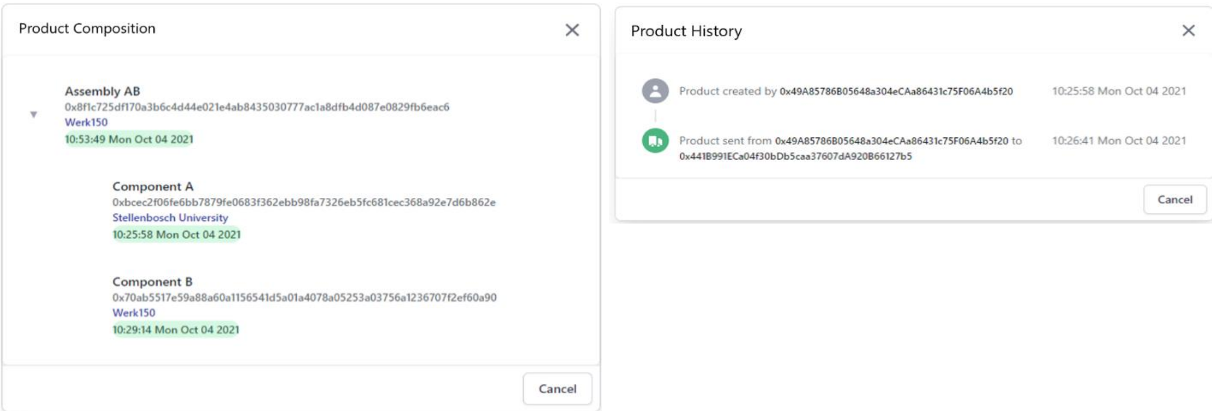

Fig. 4. Visualization of a product’s composition and history.

A logical coupling of aggregated tokens ensures that all tokens are being constrained to the same place at the same time when merged. If the owner of ‘Component AB’ sends the token to a new owner, this owner strictly speaking also owns ‘Component A’ and ‘Component B’ that are logically coupled to ‘Component AB’. The tokens created with the token blueprints can be sent, transformed, or aggregated in order to map the core supply chain events of their physical counterparts. As shown in Figure 4, in addition to the event history of each token, the smart contract also maps each token’s composition. These functionalities allow study groups to flexibly apply the application to elaborated scenarios in the production and supply chain domain.

3. Result

The presented teaching concept to convey the benefits of blockchain-based applications in supply chains and production consists of two stages. The first stage describes a methodical workshop, which playfully teaches the complex functionalities of blockchain technology and decentralized applications. The second stage involves a prototypical application in an industry-oriented environment such as learning factories to put the acquired knowledge into practice. The application used in the teaching concept incorporates an architecture that supports the flexible and dynamic addition of stakeholders and tokens. Like this, students can apply it to a wide variety of application scenarios in the production and supply chain domain. The deep understanding of the blockchain technology generated during the workshop stage in combination with a flexibly adjustable prototypical application enables students to extend the application itself through new and creative approaches and promotes the development of completely new application scenarios.

4. Conclusion, Remarks, and Outlook

This paper proposes a novel teaching concept to convey the benefits of blockchain-based applications in supply chains and production by means of learning factories. Initial experiences with the teaching concept show that in particular the execution of the workshop stage before implementing the application leads to significantly better results regarding understanding and applying blockchain scenarios in production and supply chain management. It allows knowledge to be imparted to the learning groups in a playful way leading to the advantage that differences and benefits of blockchain applications compared to other technologies are clearly evident to the participants. The concepts can also be applied when educating industrial partners in terms of developing industrial blockchain applications. In this way, it can be conveyed that in most cases it is not necessary for companies to develop their own blockchain platform, but rather to develop applications drawing on existing and established networks. This represents an important technological foundation towards blockchain-based production and supply chain ecosystems. In the next steps, the solution will be increasingly automated. Manual inputs and the manual triggering of functions will be replaced by Internet of Things (IoT) devices in order to reduce the error rate and increase the overall integrity of the solution. Further research is currently being conducted in transferring data securely and reliably from IoT devices to smart contracts.

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