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Designing A Blockchain-Based Digital Twin For Cyber-Physical Production Systems

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Abstract

Trust in all processes on the shopfloor is crucial for the success of a production process, especially in cross-company scenarios such as shared manufacturing, in which independent parties interact with each other. A cyber-physical production system (CPPS) contributes to the vision of a decentralized, self-configuring and flexible production. Digital twins (DTs) can visualize the material, information and financial flows in real-time and improve the process transparency of such production systems. The efficiency of digital twins depends on the integrity of the provided data, especially if data is shared across company borders. Due to its characteristics such as immutability and transparency, blockchain technology (BCT) provides a basis for establishing the desired trust in the systems on the shopfloor. This paper proposes the design of a BCT-based DT in CPPS. The design is demonstrated by a prototype including smart contracts attached to a CPPS simulation model visualizing the information and material flow. Tasks are decentrally allocated, deployed and safely documented via blockchain. The demonstrator is revealing supplementary benefits in terms of transparency provided by the BCT. This paper further examines whether BCT can enrich existing solutions and provide a reliable information basis for profound data and process analysis.

Keywords

Cyber-Physical Production System; Blockchain; Negotiation; Digital Twin; Manufacturing; Transaction

1. Introduction

Cyber-physical systems (CPS) are the result of merging virtual and physical entities, whose interplay is enabled by embedded hard- and software attached to its respective physical counterpart [1]. Transferred to the shopfloor, cyber-physical production systems (CPPS) are a promising approach to fulfill the vision of a smart factory [1], which is realized through the interplay of CPS and so-called digital twins (DTs) [2]. However, the visibility enabled by DTs is impeded by restricted data accessibility or lack of data collections [3].

Due to its potential of '*provid*[ing] *validated, immutable transactions, i.e. database updates* […]' [4, p.1546], blockchain technology (BCT) is herein considered. The interplay of its inherent consensus mechanism, cryptographic protocol and distributed storage lays the ground for an immutable and transparent data storage to achieve data and process integrity [4–7]. Blockchain itself can be adopted for '*redesign*[ing] *informational and financial flows, both of which supplement physical flows in a supply chain*' [8, p.10].

A BCT-based DT promises a reliable real-time visualization of these flows for CPPS. Against that backdrop, the underlying research question is how to design a BCT-based DT for CPPS. For doing this, a methodology for conducting and carrying out Design Science Research (DSR) proposed by [9] is applied here. Our contribution is structured as follows:

- Introducing the addressed problem and objectives (**chapter 1**)
- Deriving the state of the art of DT, BCT, CPPS and its intersections (**chapter 2**)
- Designing a BCT-based DT for CPPS (**chapter 3**)
- Demonstrating and evaluating the prototype (**chapter 4**)
- Communicating design implications (**chapter 5**)

2. State of The Art: Conjunction of CPPS, Digital Twin and Blockchain Technology

The starting point for the design process is the derivation of design knowledge about the three investigation units CPPS, DT and BCT. In each subsection, the investigation unit is introduced, followed by a summary of previous research dealing with the intersection with the other two units. The findings form the design knowledge for the subsequent designing process (**chapter 3)**.

Cyber-Physical Production System (CPPS)

Increasing product variety and new technological developments have inpired the idea of CPPS that allow for automated, flexible and self-configuring production [10]. However, autonomous, decentrally organized CPPS have to deal with high levels of complexity and much uncertainty regarding cross-company interactions as well as issues with data security and robustness against failures [11].

In a CPPS, heterogeneous entities such as mobile robots, smart bins and machines interact with each other. These entities do not necessarily belong to the manufacturer, but can be provided by several independent parties such as vendors or lessors [12]. Transparency with regard to process data (e.g. usage data) is mandatory for a smooth collaboration and reduced coordination effort in terms of payment. Furthermore, as the entities utilize different software, universal interfaces are necessary to ensure a comprehensive and transparent overview across all processes [13]. However, conversing between different interfaces is prone to errors, which could cause loss of information. Besides, unauthorized devices with reading and writing rights could manipulate data such as order data. Without precise, secure and tamper-proof documentation these failures and manipulations affect the transparency of the CPPS for the involved parties [14].

Additionally, third parties such as customers and suppliers call for transparency about the progress of an order or the status of the warehouse for procurement. Trust in the manufacturing process determined by correct and sufficient quality control and punctual delivery is important for a successful customer loyalty [15]. Thus, a lack of transparency can result in inefficient procurement processes and dissatisfied customers [16]. It leads to a higher amount of overhead as costs of robots or smart bins cannot be assigned to the causative principle. Non-transparent process documentations and overheads affect the reduction of process costs and the precise determination of prices and profits of single products [17].

Digital Twin (DT)

To cope with some of these challenges, a DT can be used in a CPPS. The term DT was introduced by [18] in 2003 and describes the precise representation of a physical object or system in the digital (cyber) world [18]. Physical and digital systems can affect each other [18,19], which leads to a merge of the physical system and its digital representation [20]. Further distinctions of DT have been made by [21], in which the DT consists of a bilateral information flow between a physical object and its digital representation [21]. Extensive research of applying DTs into the production field on shop floor level can be traced back to the elaborations of [22,23]. The authors propose a five-dimensional DT structure, which consists of the physical entity, its virtual pendant, services between both entities, data of the DT and the connection of different parts of a DT [23]. Following [24], two starting scenarios for DT development can be distinguished. In the first scenario, neither a physical object nor a DT of such an object exists, whereas the second scenario concentrates on extending an existing physical object that does not have a DT yet. Each scenario passes the design, development, operational and dismissal phase [24].

DTs can be applied for data analysis and simulation to reduce costs, predict failures and prepare for unexpected events. Simulating specific states of the system or adding new components is also possible with the DT without changing the physical system. This saves costs and time, for example when developing a prototype or testing different production scenarios. The DT is also used for 2D or 3D visualisation of production processes [25]. Despite the potential of using a DT in CPPS, several aspects remain critical in a combined system. The DT might not display the physical part of the CPPS correctly due to a lack of transparency and documentation. Besides, as explained above security such as device authorization is a critical issue in a CPPS. Manipulated data of the physical system influences the DT due to the interplay between the physical and digital system such as the use of sensors [25]. Therefore, the DT is highly dependent on reliable data from the physical world, whereas the physical system is dependent on the correct input from the digital world.

Blockchain-Technology (BCT)

One approach to the solution is BCT. According to DIN SPEC 16597, the term blockchain can be described as a '*distributed database that is practically immutable by being maintained by a decentralized P2P* [peer-to-peer] *network using a consensus mechanism, cryptography and back-referencing blocks to order and validate transactions*' [26, p.8]. BCT can be subordinated to the Distributed Ledger Technology (DLT) as a DLT concept [27]. A condensed overview of the most mentionable challenges and benefits related to blockchain is proposed by [28]. Following [29], BCT is characterized by its permanence, immutability, disintermediation and transparency and receives closer consideration due to these trust-inherent characteristics enabled by the interplay of consensus mechanism, decentralization and cryptography [4,7]. An emphasis in terms of establishing trust in intercompany networks enabled by BCT is proposed by [30].

A proposal for a BCT-based engineering framework is described in [5], which consists of technological components on an infrastructure layer, enriched by an environment layer, an application layer, an agent layer, a behavior layer and the trust frontier, which separates the latter ones and addresses the trust issues between the physical system and its virtual model. The interplay of immutability and transparency forms the basis for process and data integrity on the application layer, in which the data integrity consists of the degree of completeness and immutability of data and the process-integrity encompasses the rule-compliant execution of processes [7]. In trust-relating literature, the term integrity describes the '*perception that the trustee adheres to a set of principles that the trustor finds acceptable*' [31, p.719]. In conjunction with the ability and benevolence, it represents one of the '*factors of trustworthiness'* [31, p.717]. The authors of [32] assume that an increase in integrity can be enabled by smart contracts as long as they limit the scope and expectation of opportunistic behavior. Smart contracts can be seen as '*autonomous interacting pieces of code* […]' [4, p.1543], whose execution is based on predefined rules and which allow the omission of intermediary instances, that, in turn, saves transaction costs [4,33].

Referring to [29], '*the process of creating a 'digital twin' of a physical good on a blockchain is called tokenization* [in which] [...] *Users can exchange the ownership of these digital representations, or tokens* […]' [29, p. 3]. DLT allows the virtual representation of the properties or behavior of the reference object, which can be either a person or an object [34]. An example, how a DT can be connected to the Ethereum blockchain is shown in [35], where a three-layered concept is proposed, in which non-fungible (ERC721) Ethereum tokens are connected to DTs and enriched by smart contracts, which '*allow automatic material flow decisions in the manufacturing system*' [35, p. 253].

Towards a DLT-based DT for CPPS

In a previous elaboration on CPPS and DLT, a literature research led to the assumption that DLT enriches previous (de-)centralized infrastructures in terms of security and processing [36]. Furthermore, integrating a BCT-based DT in a CPPS provides a solution for the challenges in such production systems [37,38]. It can be used to interact with the system and carry out payment or replenishment orders. Besides, it does not only present the current state of information in the system, but also offers a complete and tamper-proof history of all states the system has been in so far. Thus, it serves as the basis for sound decision-making and profound process analysis [39] and provides reliable data for AI approaches such as the prediction of failures or peak loads [40]. Furthermore, via BCT and a DT, data exchange within the CPPS and between external stakeholders such as customers and suppliers can be standardized and simplified [41].

The potential of combining CPPS with BCT has been recognized in literature: Smart contracts can provide a distributed and immutable record of transactions [42] by checking for fulfilled requirements and automatically reacting to that. Based on this, pay-per-use models can be realized [43,44]. Several publications either propose theoretical concepts for a BCT-controlled CPPS [38,45,46] or present small-scale implementations of single components of a CPPS [37,47]. These also include, for example, blockchain-based auctions usable for task allocation [48,49]. It is evident from the researched literature that BCT provides transparency in CPPS due to its inherent characteristics. However, the triad of CPPS, BCT and DT has only been researched in few publications on a conceptual level [40,50]. As of now, it remains unclear how to design and implement the BCT-based DT to realize such potential.

3. **Designing the BCT-based DT of a CPPS**

For designing and implementing a DT, the prerequisites under which the DT is developed and its lifecycle have to be considered. Referring to [24], we focus on the second scenario as our DT extends an existing CPPS in our research hall. The focus is set on the design phase with regard to the DT of an excerpt of a physical production system and its connection to a blockchain. Our design of the DT is based on the five dimensions of a DT proposed by [23]. We combine these dimensions with the blockchain engineering framework proposed by [5] with intention to overcome the challenges of process and data integrity. The merged model, transferred to CPPS, is shown in **Figure 1.**

The **behavioral layer** consists of a tangible CPPS with its entities such as machines and mobile robots and represents the DT dimension of the Physical Entity. This tangible CPPS is represented on the **agent layer** by one or several DTs (**virtual entity**) enabled by simulation tools [51]. The trust issues between the agent layer and the behavioral layer can be described by the lack of process and data integrity as trust-inherent characteristics [7]. Blockchain can be attached to the DT of the CPPS and supports the visibility of the state conditions enabled by smart contracts on the **application layer** [4,5]. The interplay and connection of the physical and virtual entity as well as the blockchain represents the dimension of the **connected digital twin**, in which information are exchanged in a bidirectional way between the layers.

The application layer itself ensures the interoperability between the blockchain framework and the agents, which can be either a human frontend interaction or a machine-API-interaction of a cyber-physical entity acting as an agent. Transferred to the scenario of a CPPS, smart contracts can be foreseen for executing the transactions inside the negotiation scenario on the shop floor. This drives the automatizing process forward and allows agents to act autonomously. These interactions are part of the DT dimension called **services,** which also includes the interoperability between the physical and virtual entity by synchronizing them in real-time. The physical entity can report its initial states of the system to the virtual entity and the virtual entity can in turn influence the **physical entity**, for example by returning a determined resource allocation. Other services, for instance, can be provided for monitoring of energy consumption in the physical entity or testing of certain functions in the virtual model.

On the **environmental layer**, the policies of the whole framework can be defined, which can be for example rules for task allocation, the definition of roles with certain access rights and restrictions, transaction relevant tokens and the determination of data captured and stored within the transaction log. This is part of the **digital twin data,** which comprises all data from the physical and virtual entities and services and, thus, includes information from every layer. For the CPPS, data from the information, material and financial flows can be part of the DT data. Especially the financial transactions extend the data of the physical system and its virtual counterpart. These include, for example, tenders, bids, order placements and payments.

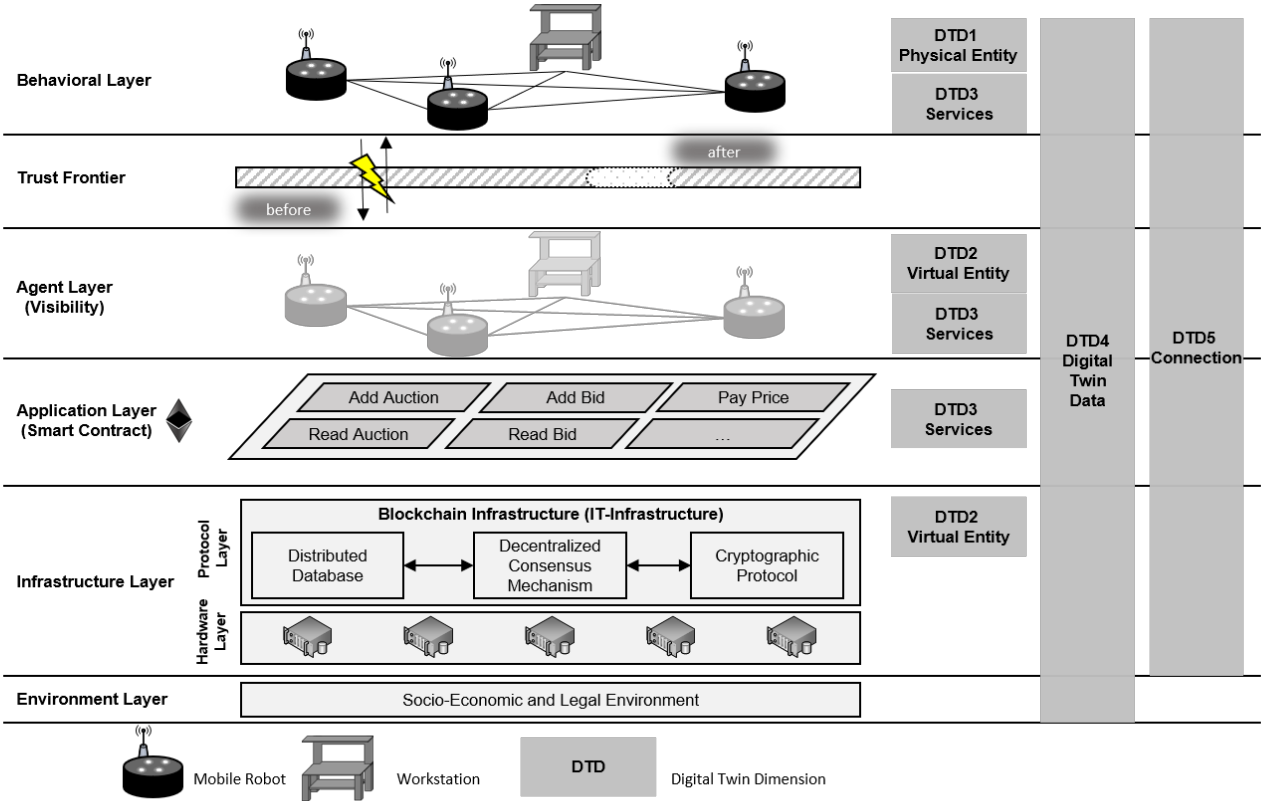

Figure 1: Framework for designing a BCT-based DT for CPPS (based on [5,23])

4. **Demonstration and Evaluation**

The BCT-based DT of a CPPS to be demonstrated in this contribution is located in the manufacturing context as described by [52,45,53]. In this tangible CPPS, individually configurable drones are manufactured in a decentrally organized matrix production system [54]. The system consists of several entities such as workstations, mobile robots, smart bins and workers that solve task allocation by negotiation. The prototype comprises an excerpt of this production system. The prototype illustrated in **Figure 2** focuses on the task allocation between a workstation and several mobile robots, which provide material for the workstation.

In the following, the prototype considers the agent and application layer with regard to the virtual entity, services, DT data and the connection between the layers. The agent layer of the prototype is replicated with the game engine Unity[1], which also serves as the virtual entity. For visualization purposes, the DT is created and animated in 3D. Inside the Unity scene, an additional 2D dashboard depicts system information such as the current state of a mobile robot in real-time. The virtual entity is supplemented by a blockchain testnet based on the Ethereum framework[2]. The transaction data is stored inside a blockchain and shown in a

[1] https://unity.com/

[2] https://ethereum.org/en/

frontend layer, which is provided by a Web3-React interface[3]. Unity and Ethereum are merged via Nethereum[4], an open-source API for integrating the Ethereum blockchain into .NET applications.

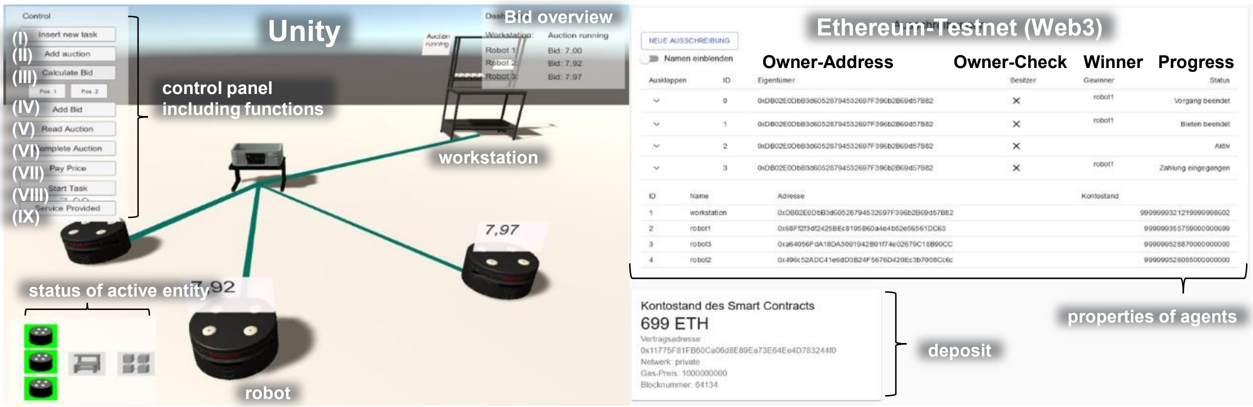

Figure 2: Sketch of the prototype of the merged visualization with unity (left) and blockchain (right)

The prototype is embedded in a scenario comprising the request of material, followed by settlement and task allocation, task fulfillment and payment. The decentralized task allocation follows the principle of rule-based bidding with a reverse first-price-sealed-bid auction (FPSB), in which multiple sellers compete for a single buyer without knowing the bids of the competitors [49]. In this context, robots are offering their transportation services, which are requested by a workstation. For simplicity, the bid of each robot is determined by its distance to the workstation. The workstation chooses the lowest bid, which is the closest robot. Smart contracts are based on the programming language Solidity[5]. As **Table 1** shows they provide call- and send-functionalities for the control of the CPPS.

This prototype shows the relevance of the DT in CPPS with integration of BCT. In our system, the DT based on a virtual entity in Unity allows an extensive visualization of the production system as well as its material and information flows. A real-time environment provides the user with an overview of the whole system at any time to make well-founded decisions. Furthermore, the visual interface allows a human-machine-interaction with the virtual entity. This is a decisive step for successive testing and understanding the cause-effect relationships of DT during the development phase and it is also a mandatory part for the basic DT archetype [51]. Thus, the prototype can be classified as an '*Enriched Digital Twin*', which '*enriches its database by preprocessed data from supplementary systems* […]' [51, p.12].

Additionally, the Unity model allows an analysis in time-lapse without the need of validating transactions in a blockchain. Physical behavior can be replicated and negotiation-relevant data such as the bids of the robots can be calculated faster. The virtual entity enabled by the Ethereum framework provides the requested transparency and process as well as data integrity. As it would not be efficient to store all data on a blockchain due to the necessary computing power and storage, only data with high need of integrity has to be stored on the blockchain [46]. Thus, the blockchain does not replicate the holistic DT in Unity. It rather enriches it by providing several functions to ensure compliance and transparency and promotes the virtual entity to the next level of an enriched DT archetype [51].

The Web3-frontend and the blockchain allow for selective control of access rights in the CPPS. Only verified entities can enter the system and add auctions or bid on auctions, which means that they have to belong to the requested group of entities or that they have to have a certain amount of Ether to be able to pay for a tender. These features are considered in the provided smart contracts, for example the `addBid` function.

[3] https://betterprogramming.pub/blockchain-introduction-using-real-world-dapp-react-solidity-web3-js-546471419955

[4] http://docs.nethereum.com/en/latest/

[5] https://docs.soliditylang.org/

Requirement statements embedded in the functions prevent entities from bidding on their own auctions and check if the entities fulfil the requirements such as necessary rights to call these functions. Hence, rule compliant negotiation mechanisms within the CPPS can be ensured and process integrity can be guaranteed. As all transactions are recorded safely and completely, they can be used to automatically assign costs according to the causative principle and to ensure that the respective payments are completed. If an auction is completed and the winner is selected, the owner of the auction will deposit the amount of the bid in Ether in the smart contract. The winner is informed and fulfils its task. Once the task has been fulfilled, the smart contract automatically releases the stored amount of Ether as payment for the winner. This measure creates trust for both entities, as the winner has certainty about the fulfilled payment, whereas the owner has confidence that it will get its Ether back in case of failure. The blockchain keeps a complete and tamper-proof history of transactions including bidding information, owners of auctions, selected winners and deposits, which persists over the limited runtime of the Unity model.

Table 1: Overview of functionalities

No.	Function	Input Parameters for Smart Contracts	Supported by virtual entity
(I)	`insertNewTask`	-	Unity
(II)	`addAuction`	`(privateKey)`	Ethereum
(III)	`calculateBid`	-	Unity
(IV)	`addBid`	`(privateKey, auctionNumber, bid)`	Ethereum
(V)	`readAuction`	`(privateKey, auctionNumber, bid)`	Ethereum
(VI)	`completeAuction`	`(privateKey, auctionNumber)`	Ethereum
(VII)	`payPrice`	`(privateKey, auctionNumber)`	Ethereum
(VIII)	`startTask`	-	Unity
(XI)	`serviceProvided`	`(privateKey, auctionNumber)`	Ethereum

5. Conclusion and outlook

This contribution focuses on the triad of CPPS, BCT and DT to enhance transparency, and process and data integrity in CPPS. A concept of a BCT-based DT for CPPS is designed and demonstrated. Based on reusable design knowledge about each component, a consolidated framework for designing BCT-based DT for CPPS is proposed. The demonstration of a prototype of a BCT-based DT for CPPS in the manufacturing scenario confirms that the transparency and integrity within the system can be increased. However, the elaboration underlies certain limitations. More profound research of additional challenges concerned with BCT such as security, privacy or scalability is required [28], especially with CPPS and DT. The methodology followed allows further revisions during the build and evaluate cycle [9]. In future, we will extend the presented prototype to the whole system in terms of the scope and variety of agents and corresponding transactions. This includes a more resilient quantitative analysis regarding validation time and transaction costs as well as scalability. Other open aspects are the integration of the physical entity in the development phase and the elevation of the DT to a higher level of archetype by integrating autonomous BCT-based control of the extensive CPPS [51]. The broadly accepted value propositions of BCT and DLT as for example trustworthiness, credibility, immutability, data sovereignty or decentralization pave the way for a next evolution level adding a Financial DT component to the concepts of DTs of CPPS on the shopfloor. Financial DTs acting as agents of a company´s Finance Department and interacting with their digital counterparts on the shopfloors might have a huge potential to trigger innovative and highly efficient working capital and asset finance solutions. We encourage researchers and practitioners in the fields of Information Systems and Logistics to adapt the proposed concept to derive design implications in the fields of BCT, DT and CPPS.

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