DOI: 10.2195/lj_Proc_kraemer_en_202112_01
URN: urn:nbn:de:0009-14-54238

Towards a Concept for Blockchain-based Cyber-Physical Production Systems

Ein Konzept für ein Blockchain-basiertes Cyber-Physisches Produktionssystem

***Larissa Krämer*[1]**
***Rico Ahlbäumer*[1]**
***Jens Leveling*[2]**
***Peter Detzner*[2]**
***Marius Brehler*[2]**
***Michael ten Hompel*[1,2]**

[1]*Chair of Materials Handling and Warehousing*
Faculty of Mechanical Engineering
TU Dortmund University
[2]*Fraunhofer Institute for Material Flow and Logistics*

This contribution evaluates the feasibility of blockchain technology for processes of a cyber-physical production system (CPPS) using a decision framework. The evaluation is based on an implemented CPPS use case. Opportunities for the use of smart contracts are identified and two exemplary smart contracts are designed. To integrate the heterogeneous and resource-constrained IoT devices of a CPPS, three levels of connection to the blockchain are identified and applied to the use case. This work contributes to the implementation of an extensive blockchain-based CPPS.

[Keywords: Blockchain, Industry 4.0, smart contracts, cyber-physical production systems, embedded systems]

Dieser Beitrag evaluiert den Einsatz der Blockchain-Technologie für Prozesse eines cyber-physischen Produktionssystems (CPPS) anhand eines Entscheidungsrahmens. Die Evaluation basiert auf einem bestehenden CPPS Anwendungsfall. Es werden Möglichkeiten für den Einsatz von Smart Contracts identifiziert und zwei beispielhafte Smart Contracts entworfen. Um die heterogenen und ressourcen-beschränkten IoT-Geräte eines CPPS zu integrieren, werden drei Ebenen der Anbindung an die Blockchain identifiziert und auf den Anwendungsfall angewendet. Diese Arbeit trägt zur Implementierung eines umfang-reichen blockchain-basierten CPPS bei.

[Schlüsselwörter: Blockchain, Industrie 4.0, Smart Contracts, cyber-physische Produktionssysteme, eingebettete Systeme]

1 Introduction

Manufacturers face the challenges of increasing production variety and short delivery times due to increasing customer requirements [TsH14]. Among other things, this evolution is driven by the needs and expectation of manufacturers and customers. Nowadays, customers expect personalized products, whereas each product can be configured by the customer. This is also known as lot size one [ABB11]. In addition to that, manufacturers demand a high utilization of their machines [DBL17], but also the ability to handle unforeseen events and other challenges [KOR10]. To conquer these challenges, cyber-physical production systems (CPPS) have emerged and attracted a lot of attention since [MON14]. CPPS enable self-configuring, flexible and automated production [MON14] and therefore also offer potential for a scalable production [WEE16]. However, this also increases the complexity of decision making. One way to cope with this increasing complexity is the utilization of decentralization [HPO16].

A CPPS consists of numerous heterogeneous entities, such as humans, automated guided vehicles (AGVs), machines, sensors and other resource-constrained devices. These devices differ, for instance, in their energy consumption, storage or computing power [RMC18]. They are used to gather data from the physical environment, while the interaction with the physical and digital environment is performed via actuators [DIL17]. This generated data is collected, stored and needs to be evaluated. As a result, scalability needs to be considered [WEE16].

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Furthermore, services and devices in a CPPS are not provided by a single vendor. Therefore, major challenges such as cross-company interactions, data security or robustness against failures arise [LAS19]. To address these challenges, blockchain technology can be integrated into CPPS. It enables participants in the blockchain network to interact with each other without an intermediary or the need of a central trusted party [CCK18]. However, with the integration of blockchain technology into CPPS new challenges emerge. To avoid potentially high network communication, relevant processes for the use of blockchain technology need to be identified. In addition, the limited resources of the incorporated IoT devices require special attention when using blockchain technology.

Based on a use case for the blockchain-based CPPS, we analyse the feasibility of blockchain technology using a decision framework. We identify opportunities for smart contracts and design two exemplary ones. To integrate these heterogeneous devices, we differentiate three levels of connection to the blockchain, apply them to the use case and specify the information flow from an IoT device via an intermediate layer to the blockchain.

The remainder of the paper is structured as follows: Section 2 gives an overview of the related work regarding blockchain technology and blockchain-based CPPS. Furthermore, decision frameworks to evaluate the feasibility of blockchain are presented. In section 3, we apply one of these decision frameworks to the use case and give examples for smart contracts. Subsequently, section 4 provides technical details on how to integrate IoT devices into the blockchain. Finally, section 5 comprises a conclusion and points out further research opportunities.

2 Blockchain technology

A blockchain is a series of immutable and decentralized records of data, managed by and distributed to any participants in the involved network [Nak09, NBF16]. Every participant has a complete copy of the blockchain, making it more secure against single-point-of-failure and almost impossible to change data, as each copy would have to be changed [PPS15]. To establish the correctness of each block, a blockchain uses a consensus mechanism [MXZ17]. This mechanism determines which participant may add another block based on, for instance, their computing power or their share of the network. Due to this consensus, blockchain participants can trust in the information in the blockchain, even if they do not know or trust each other. Another feature of many blockchain frameworks are microservices, which are executed in the blockchain and therefore validated on-chain. These services are called smart contracts [But13]. The terms of agreement are implemented directly into the code and any needed assets can be saved into the blockchain as well. When the terms of agreement are met, the smart contract is executed and outputs a result that is written into the blockchain. This allows participants of the blockchain automatic, trusted and irreversible transactions without the need for an intermediary.

2.1 Blockchain-based CPPS

Integrating blockchain technology into a CPPS provides a potential solution for the challenges of cross-company interaction and security in such a system. Transactions are stored in a transparent, distributed and tamper-proof way allowing entities to access this information and to trust the data. This provides, for instance, a distributed and immutable record of robot transactions [SmT18]. Smart contracts can be used in a publish/subscribe network giving robots the possibility to reconfigure on the fly [SmT18]. To further increase the security of the system, blockchain technology can also be used to manage a register of authorized entities in a CPPS [RMC18] and to implement decentralized marketplaces and improve pay-per-use solutions [GSC20, GLW20]. Thus, blockchain technology can enable trustworthy interactions between various stakeholders and devices in a CPPS [LAS19]. The usage of blockchain technology in a CPPS is proposed and tested with the Ethereum network as a backbone [AFK18, ASK18]. The authors develop a use case for manufacturing, but also point out open issues regarding performance and security as areas of further research. They consider a small use case with Raspberry Pi's, which are more capable than most IoT devices, and a low number of participants. The authors of [BSK20] suggest the integration of blockchain technology into their CPPS to solve its challenges. However, the authors do not go into detail which processes in their system benefit from that and do not describe a concept for the blockchain-based control.

In a CPPS, devices communicate with each other. Most devices in an Internet of Things (IoT) setting are resource-constrained and have limited computational power [SPK12]. This is still a current research topic in the context of blockchain [KSW21]. The authors of [SaC19] compare various blockchain consensus mechanisms to evaluate their suitability for IoT devices. They also discuss increasing security for IoT networks through blockchain. To integrate IoT devices into blockchain, different approaches are proposed based on resource restrictions and the ability to execute smart contracts. Devices with low computing power which cannot execute smart contracts can be connected via a base station which handles the blockchain connection [HaK19]. More powerful devices which can run smart contracts are connected directly to the blockchain using a remote trusted blockchain node [SiB18]. To avoid this, another approach turns IoT devices into Light Nodes [SGH20]. A Light Node is a smaller blockchain participant, which only holds device-specific data of the blockchain, without sacrificing validation. Two of these approaches are used in our work as described in section 4.

However, the involvement of many entities in a CPPS requires a scalable solution to ensure that every interaction is documented in reasonable time [APR18]. Additionally, the latency of the solution is important for CPPS, as those are near real-time systems. In particular, this applies to decision processes within the CPPS to avoid delays of the entire system [AKS18]. The continuous exchange of information between heterogeneous entities and stakeholders requires a high transaction rate and creates network traffic and data. According to [RMC18], there is no need to store all data in the blockchain to avoid additional network communication and storage space.

2.2 Frameworks to evaluate the Feasibility of blockchain

To evaluate which information should be stored in a blockchain, several authors propose decision frameworks from different perspectives such as a management point of view [PRB19] or a more general approach across several use cases [LXC17, CCK18]. Some frameworks are specifically tailored to use cases such as construction [HuD20] or IoT [PEH18]. [CCK18] compare blockchain and traditional databases and, from this, derive a decision framework consisting of two parts. The first part allows to evaluate the suitability of blockchain for the use case, whereas the latter part determines which blockchain platform to use and if data should be stored on-chain or off-chain. At this step, we consider the first part of the framework. The first two criteria check for the number of involved stakeholders and if there exists a trust deficit between those stakeholders. In the framework, the stakeholders are called parties. A single stakeholder using blockchain would only create overhead [PEH18] and thus, blockchain is more useful in scenarios with multiple stakeholders. Generally, multiple interacting stakeholders with trust deficit resort to a trusted third party and, thus, also accept risks [CCK18].

The framework of [CCK18] suggests to never use blockchain for scalability critical processes, as many blockchain implementations, such as bitcoin, scale poorly [CDE16]. For CPPS, scalability is always an essential requirement [APR18], which might exclude any integration of blockchain according to [CCK18]. However, the authors of [RDC21] provide a promising approach to strengthen scalability within a blockchain network.

2.3 Research Gap and Approach

The reviewed literature indicates a research gap that is twofold. On the one hand, the feasibility for blockchain in CPPS processes and necessary smart contracts have not been examined. On the other hand, it remains unclear how to implement these processes regarding resource-constrained IoT devices.

We utilize an implemented CPPS use case and reveal the potential of blockchain technology using a decision framework. For this, we select specific processes of the CPPS with regard to cross-company interaction and apply the five steps of the framework to each process. Based on this, we derive mandatory and optional data to be stored in the blockchain and design two exemplary smart contracts. To handle the integration of resource-constrained IoT devices into blockchain, the IoT Broker can be used in the underlying research project. The IoT Broker is described in more detail in chapter 4. In general, more research is needed on whether IoT devices and which of the messages need to be integrated into a blockchain.

3 Feasibility of Blockchain-Technology

To design the integration of blockchain into a CPPS, we use the CPPS developed and implemented in a test bed of the chair of Materials Handling and Warehousing of TU Dortmund [BRB19, BSK20, BMK20]. In this exemplary CPPS, individually configurable drones are manufactured. It comprises four types of entities, namely workstations, bins, AGVs and workers. Workstations and workers are equipped with tablets and smartphones. Each entity can be from another company. In the following, we assume that the AGVs are leased. In addition, customers interact with the CPPS by placing orders on a web application. Each stakeholder is interested in maximizing their own profit and might have competing interests. The lack of transparency and tamper-resistance in the CPPS leads to trust issues between them. Therefore, a trustworthy documentation of cross-company interactions is necessary. Before integrating blockchain, we briefly introduce the use case.

The manufacturing process is decentralized [BLS17]. The manufacturing steps are split up into work steps according to a specific order of precedence [BRB19]. Figure 1 visualizes the procedure of one work step, starting with the task agent. This agent publishes requests for each possible work step to several workstations, which request workers and material to complete an assembly step. Workers place their offers, whereas the bins with material issue further requests for transport to AGVs. The AGVs answer the requests and offer their services. The bins aggregate these offers and send their offers to the workstations, which aggregate those with the offers from the workers. At last, the task agent receives the offers and selects the most suitable one. A detailed description of the involved processes is given in [BSK20].

We focus on processes with cross-company interactions as they are most likely to benefit from blockchain technology [LAS19]. To simplify the system further, we limit our considerations to processes directly involved in the interaction of the entities of the CPPS. Thus, we do not consider processes such as reordering or sending the product to the customer.

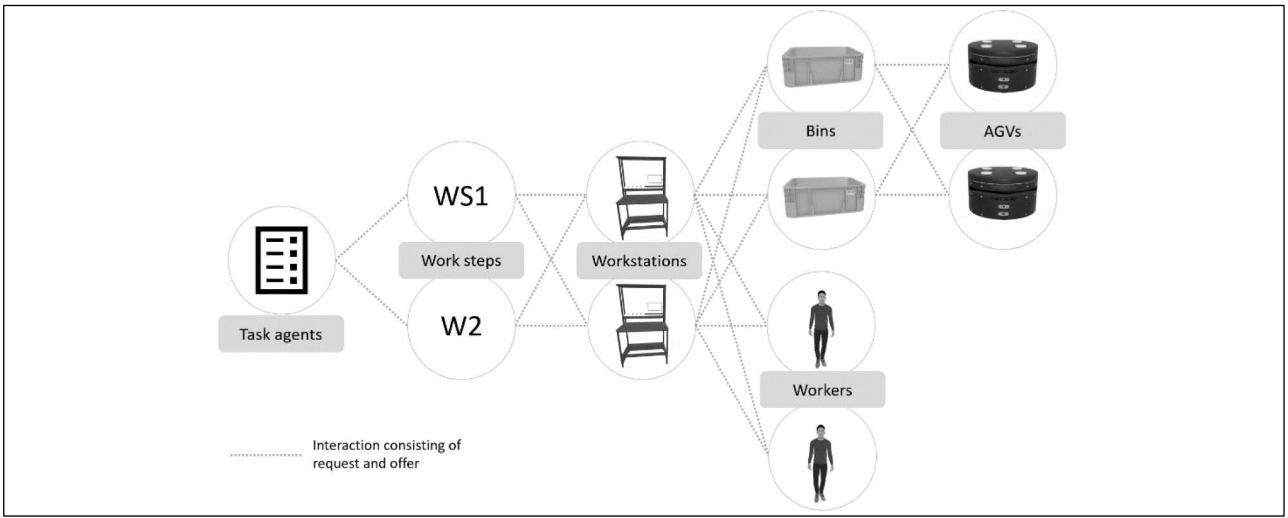

Figure 1. Interaction in the CPPS following [BSK20]

Table 1. Evaluation of suitability of CPPS processes for blockchain technology following [CCK18]

Processes in the CPPS	Are there multiple parties?	Is there any trust deficit among parties?	Is there any trusted third party?	Should the record of transactions be immutable?	Is scalability a critical requirement ?	Use Blockchain?
Place new order	yes	yes	no	yes	yes	yes
Request for resources	yes	yes	no	yes/no	yes	optional
Offer services	yes	yes	no	yes/no	yes	optional
Monitor work progress	yes	yes	no	yes	yes	yes
Payment	yes	yes	no	yes	yes	yes

In the following, we apply the framework of [CCK18] to our CPPS and design two exemplary smart contracts. One of the main benefits of blockchain technology in a CPPS is the automatic handling of payment processes on a transparent and reliable basis. Costs can be assigned to the resource responsible and, thus, administrative effort can be reduced. We use the framework with this aim in mind. Table 1 shows the results of the framework, split into a fulfilled criterion (yes), a not fulfilled criterion (no) and partly fulfilled criterion (optional).

Even though scalability should not be a critical requirement in the framework of [CCK18], section 2.2 shows, that it is always a requirement for CPPS and that new approaches deal with this challenge [RDC21]. To approve such an approach, it has to be adapted and applied to our CPPS. Thus, for now we exclude it from the final decision on the usage of blockchain. The remaining criteria are applied to the processes as following:

Customers trigger the processes in the CPPS by placing a new order for an individually configured drone. They share their interest in a tamper-proof documentation of order placement and order configuration with the production company. However, they may have a lack of trust concerning the transparency and confirmation of order placement, as information might be accidentally lost or incomplete. A trusted third party is not available. As the order placement is the key element on which every other process, including payment, is based, the transactions should be recorded in an immutable way.

An incoming order triggers the request for resources as, for example, AGVs or bins. Such a request involves multiple stakeholders like the manufacturer or others, who own any entities in the CPPS. These stakeholders do not necessarily trust each other as they might have competing interests and are directly involved with each other without a trusted intermediary. They might be interested in the decision process for the selection of a specific resource and, thus, have an interest in an immutable record of transactions. However, the request is not relevant for the payment process itself as it does not record any actually provided services.

Once a request has been issued, entities place offers. The involved stakeholders are the same that receive the request as described above, including customers. Those might be interested in the offers as well, as these offers serve as the basis for the decision process that determines the payment. This cross-company interaction would profit from an immutable record of transactions. However, out of several offers only one offer is accepted and the entity is used, whereas the others are rejected and the entities can answer to other requests. Only accepted offers are relevant for payments and need to be transparent for anyone involved in the payment. Even though rejected offers are not considered for payment directly, they are part of the relevant documentation of the decision processes in the CPPS that parties such as customers and lessors might have an interest in. Therefore, they might also be stored in the blockchain. A smart contract, for example as shown in figure 2, can be used to control this process. It triggers the actions as soon as a set number of entities has responded.

After the most suitable offer has been accepted, a work step is executed. A tamper-proof documentation of every completed work step provides information about the work progress of an order. It proves completed work steps such as assembly steps or quality checks and serves as the basis for payment. A smart contract can keep track of the completed work steps as shown in figure 2.

```
contract(REQUIRES sendTender() AND WAITFOR
numberOfResponses > x):
  offers <- responses

function requestResources(offers):
  bestOffer <- detBestOffer(offers)
  IF saveRejectB THEN saveReject(offers,
bestOffer)
  IF saveReqB THEN saveReq()
  return bestOffer
```

```
contract(REQUIRES newComplWorkstep):
  UNION newComplWorkStep AND complSteps

function workProgress(complSteps, orderData):
  nextStep <- checkNext(complSteps, orderData)
  IF payStep THEN payNewestStep(complSteps)
  IF nextStep IS EMPTY THEN
    createBill(orderData) AND
    IF NOT payStep THEN payAll(complSteps)
  return nextStep
```

Figure 2. Smart contracts in pseudocode for a resource request and monitoring of work progress

To trigger the payment process, either one work step or the whole assembly has to be completed, depending on the design of the process. This feature is included as an extension of the current CPPS in our test bed and illustrates the high potential of blockchain technology for CPPS. The customer as well as the manufacturer are interested in the correct billing. Money might be transferred to a wrong address or the production company might make mistakes while calculating the price. Even though a bank could function as a trusted third party for the money transfer, it cannot guarantee the correctness of the bill. As involved parties have an interest in a correct payment, the records have to be immutable. The payment should also be handled by a smart contract to automate this process and eliminate the intermediary.

The mandatory data, as shown in table 2, is important for the blockchain-based implementation of pay-per-use solutions in the CPPS. The meta data comprises any data that describe an individual entity in the CPPS. This data is mandatory to transmit work orders and payment to the entities whose offers were accepted. As these entities are owned by different companies, any payments to the entities include payments to those companies.

Table 2. CPPS data to be stored in the blockchain

Mandatory data	Optional data
Accepted offers	Rejected offers
Completed work steps	Request for resources
Meta data of entities	

There are several possible solutions for cash flow within the CPPS. One solution could be the task agent paying the entities for their services directly. In this case, the task agent divides the payment among the entities according to their accepted offers. The payment within the CPPS can either be triggered by the payment from the customer or could occur in advance to directly pay the entities for their services.

Another solution can be the entities paying each other. The figure 3 depicts this possible cash flow within the CPPS. The customer pays the task agent for the provided services including, for instance, material costs, using a smart contract. The task agent then keeps part of it as profit and sends the rest to the workstations. They keep their share and pay the bins, i.e. the supplier, for material and transport. These bins also keep their share and pay the AGVs for their services.

For payment and documentation purposes, the devices must be integrated into the blockchain. Due to the mentioned restrictions, these devices are not capable of storing the complete blockchain and, thus, cannot operate as a full node. In the next section we will give an overview of our devices and give some details on how to integrate them into the blockchain.

4 Technical implementation aspects of the blockchain-based CPPS

In our use case various devices have to communicate with a (blockchain) network. They cannot operate as full nodes due to their technical limitations. Instead, they can be connected to the blockchain with the addition of Light Nodes [SGH20]. In our CPPS, smartphones, tablets and AGVs are capable of handling a Light Node. Some devices are even more constrained and do not allow any further software functions in favour of a long battery life. Therefore, they cannot hold a Light Node. In our CPPS these are the PhyNodes [RRR15]. They handle the small load carriers (bins) to enable communication with the network and allow the display of data such as the current content. For such devices an intermediate layer is needed.

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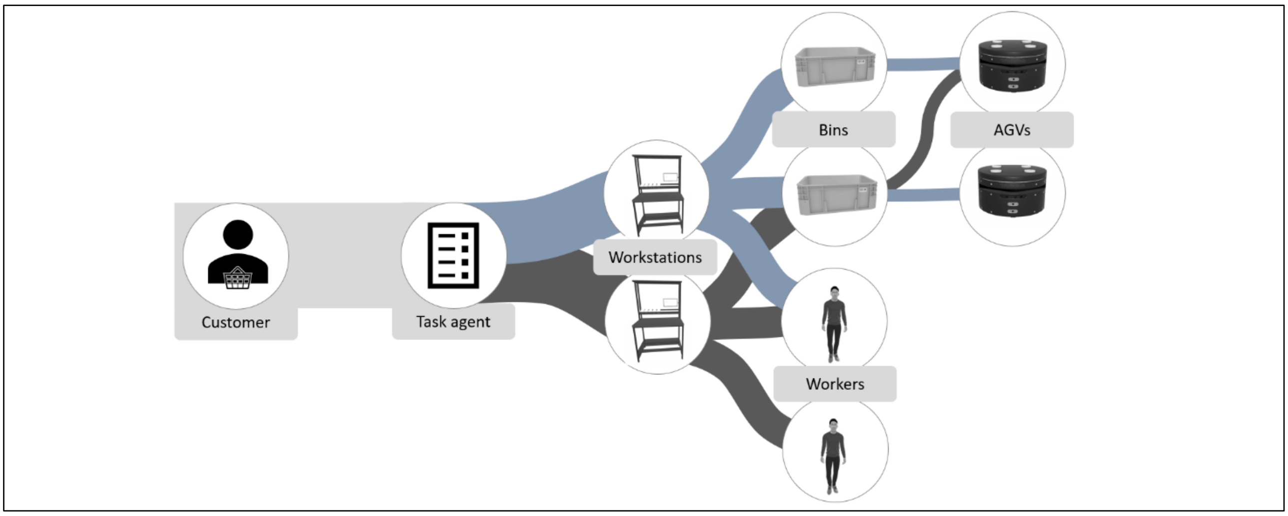

Figure 3. Entities in the CPPS pay each other for their services

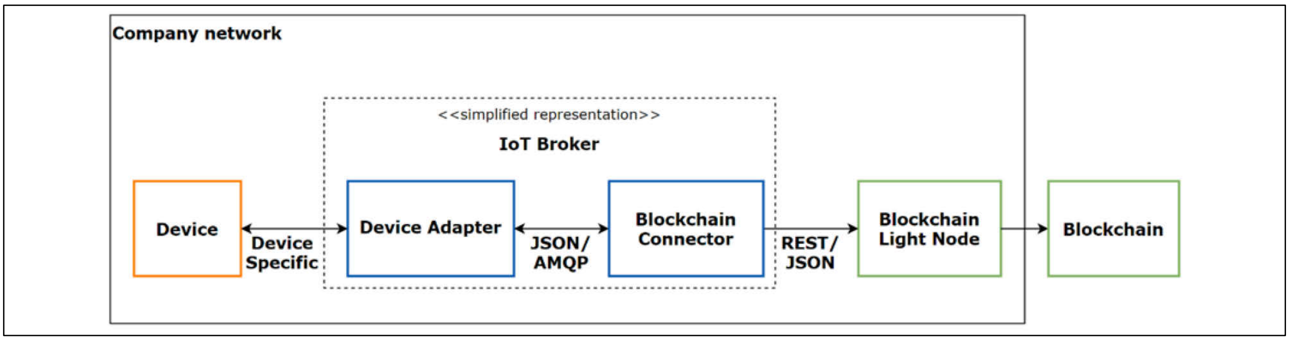

Figure 4. Information flow from an IoT Device via the IoT Broker components to a Blockchain

The IoT Broker [HHO21] represents one implementation of such a layer. It connects resource-constrained devices [LWN18] and encapsulates them and their low-level and (near) real-time capable protocols. It transforms the messages into open standards (e.g., HTTP(S), AMQP, or MQTT(S)) and into the open data format JSON. Some devices directly use JSON as data format. In this case the data transformation is omitted. The devices in our CPPS already use the same communication protocol (MQTT) and data format (JSON), and therefore, the communication towards the blockchain is unified. Building on the basic functions of the IoT Broker, the connection to blockchains is designed. The necessity of connecting the IoT Broker to a blockchain results from the mentioned restrictions for resource-constrained IoT devices. The core tasks of the IoT Broker connection to a blockchain are standardization of interfaces and message formats as well as signing of data. The connection is designed as shown in figure 4.

The blockchain integration of device data starts with implementing an adapter for each device that is to be connected to the IoT Broker. The device-specific protocols and data formats are abstracted and converted into AMQP messages with JSON as the data format. In the IoT Broker, messages are routed to different message queues using the AMQP publish/subscribe protocol. The task of the Blockchain Connector is to subscribe to relevant queues for the blockchain integration and to send the messages to the REST interface of the blockchain Light Node. This process decouples the blockchain integration from the core tasks of the IoT Broker. In simplified terms, the blockchain Connector accepts messages for storage in the blockchain from the IoT Broker. The blockchain Light Node has two functions. After receiving a message, the data of the message is signed. Then, the signed data is stored in the blockchain along with the current timestamp. The device ID is used as the key for the new entry in the blockchain and the JSON message as the value. In this entire process the device messages are not changed. This is also ensured by the fact that both the IoT Broker and the devices are in the same corporate network. Third parties can only access the data after it has been stored in the blockchain.

5 Conclusion and Future Work

A CPPS bares challenges regarding a lack of trust, transparency and security in cross-company scenarios. One approach to the solution is the integration of blockchain technology into such a system. This allows for each transaction to be immutably documented and verified by all participants in the network. Our research shows which processes in a CPPS can benefit from blockchain technology and how resource-constrained devices can be connected to the blockchain. With the analysis based on a decision framework, five processes are derived in which blockchain can play an essential role. Three of these processes require blockchain to enhance transparency and security. The other two processes can also benefit from using blockchain technology, but do not necessarily require it. Payment can be integrated into the CPPS to directly assign costs to offered services. Additionally, it is demonstrated how the heterogeneous devices of a CPPS can be connected to the blockchain. Devices which cannot be attached directly to the blockchain, can either utilize a Light Node or can be enhanced by an IoT Broker intermediate layer.

These first steps serve as the basis for future work dedicated to the implementation of an extensive blockchain-based CPPS in our test bed. However, some steps for such an implementation remain open so far. This includes a suitable blockchain framework considering the characteristics of CPPS such as scalability and near real-time processing. Furthermore, the designed smart contracts for the CPPS need to be implemented and tested. In addition, further research should be dedicated to the mechanism of requesting and offering services as well as the price negotiations involved.

6 Acknowledgement

This research was provided by the “Blockchain Europe Initiative” funded by the Ministry of Economic Affairs Innovation, Digitalization and Energy of the State of North Rhine-Westphalia (MWIDE) (Grant No. 005-2003-0068) and by the project "Silicon Economy Logistics Ecosystem" that is funded by the Federal Ministry of Transport and Digital Infrastructure.

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Larissa Krämer, M.Sc. M.Sc., Research Assistant at the Chair of Materials Handling and Warehousing, TU Dortmund University. She studied Industrial Engineering and Logistics.

Phone: +49 231 755-4076
E-Mail: larissa.kraemer@tu-dortmund.de

Rico Ahlbäumer, M.Sc., Research Assistant at the Chair of Materials Handling and Warehousing, TU Dortmund University. He studied Computer Science.

Phone: +49 231 755-4524
E-Mail: rico.ahlbaeumer@tu-dortmund.de

Jens Leveling, M.Sc., Team Lead Data Driven Logistics at the Fraunhofer Institute for Material Flow and Logistics.

E-Mail: jens.leveling@iml.fraunhofer.de

Peter Detzner, M.Sc., Research Associate at the Fraunhofer Institute for Material Flow and Logistics.

E-Mail: peter.detzner@iml.fraunhofer.de

Dr.-Ing. Marius Brehler, Senior Scientist at the Fraunhofer Institute for Material Flow and Logistics.

E-Mail: marius.brehler@iml.fraunhofer.de

Prof. Dr. Dr. h. c. Michael ten Hompel, Head of the Chair of Materials Handling and Warehousing, TU Dortmund University and Managing Director of the Fraunhofer Institute for Material Flow and Logistics.

Phone: +49 231 9743-600
E-Mail: michael.tenHompel@tu-dortmund.de

Addresses:

Chair of Materials Handling and Warehousing, TU Dortmund University, Joseph-von-Fraunhofer-Str. 2-4, Dortmund, 44227, Germany

Fraunhofer Institute for Material Flow and Logistics, Joseph-von-Fraunhofer-Str. 2-4, Dortmund, 44227, Germany