Control of Cyber-Physical Production Systems: A Concept to Increase the Trustworthiness within Multi-Agent Systems with Distributed Ledger Technology

Completed Research Paper

Andre Lebioda **Jens F. Lachenmaier**

Daniel Burkhardt

Abstract

In the course of increasing the flexibility in the area of production, industrial enterprises have been presented with cyber-physical production systems (CPPS). Through the use of autonomously acting CPPS and CPPS components – which often receive multi-agent systems as their corresponding cyber parts – new challenges arise from the need for flexibility and interoperability on the one hand and consistency, trustworthiness as well as reliability of the systems and their components on the other. In order to meet these challenges, this research paper is dedicated to the creation of a technical concept for implementing distributed ledger technology production systems. The paper follows a design-science approach, which consist of analysis, design, and evaluation. The technical concept is based on the GAIA method, which aims to design multi-agent systems and specifically addresses the security and trustworthiness of CPPS-environments. The subsequent evaluation of the concept based on discussions with experts documents its relevance and potential.

Keywords: distributed ledger technology, blockchain, cyber-physical production systems, multi-agent systems, trustworthiness

Introduction, Relevance and Business Problem

The societal trend towards increased demand for individualized products, which has to be reflected within the production environments of industrial enterprises, is leading to the so-called fourth industrial revolution or Industry 4.0.(Kagermann et al. 2013) In the course of Industry 4.0, companies implement and apply the concept of cyber-physical production systems (CPPS) as the foundation of smart factories to increase the flexibility and efficiency of their manufacturing resources.(Haas 2018) Cyber-physical systems in general consist of physical assets and their representation in the cyber world.(Lee and Seshia 2017) Within cyber-physical production systems, the components of the system communicate with each other to allocate suitable assets for the production of products.(Adolphs et al. 2016) Multi-agent systems

(MAS) offer a promising approach for the negotiations and following realization of decisions regarding production regulation and control within the cyber part of said systems.(Abbas 2017; Badr 2011; Pantförder et al. 2017)

Currently, vendors, international organizations and researchers are discussing the impact of cyber-physical production systems on security, trustworthiness and also legal liability, which also documents impressively the need for solutions to these challenges.(Adamczyk et al. 2016; Adolph et al. 2018; Böttinger et al. 2016; Hornung and Hofmann 2017; Schrecker et al. 2016) Due to the autonomy of software agents, appropriate coordination mechanisms must be established for the implementation of MAS. These coordination mechanisms help to force coherent performance at the operational level of production. The coordination within such agent-based production regulation resembles the negotiation between humans and is therefore accompanied by similar coordination problems. Therefore, integrity, traceability as well as transparency of transaction data need to be ensured for the coordination to generate security and trust in the MAS and CPPS.(Calvaresi et al. 2018) This is especially true in supply chain scenarios with multiple partners involved in production.(Brettel et al. 2014; Tjahjono et al. 2017) As recently confirmed by legal advisors in Germany, distributed ledger technology (DLT) is a viable solution for this purpose.(Duisberg et al. 2018) The following article is therefore dedicated to the development of a concept that combines CPPS, MAS and DLT. The basic idea is that by participating in the distributed ledger, agents cede part of their autonomy to the integrated coordination mechanism, thus ensuring coherent behavior. Following the recommendations of the Industrial Internet Consortium the umbrella term “trustworthiness” will be used in this paper to sum up issues of security, reliability and other related issues.(Schrecker et al. 2016) The research question that is addressed by this paper is: How can a concept be designed that improves trustworthiness in a cyber-physical production system?

Objective, Methodology and Structure of the article

The objective of this article is to develop and evaluate a technical concept for production control in cyber-physical production systems that meets the requirements regarding trustworthiness that will be defined later in detail. This paper conforms to the design-oriented information systems research, which is widespread in Europe.(Osterle et al. 2010) The approach adheres to the principles of the even larger design science research approach.(Hevner et al. 2004) The stakeholder group consists of service carriers involved in the production regulation of industrial companies, vendors of software for production control as well as resarchers and people involved in the standardization of industry 4.0 solutions. The research object is a coordination mechanism of an agent-based production regulation on the basis of DLT.

The underlying research process, which was conducted in the year 2018 and results in this paper, comprises of the stages analysis, design and evaluation (cf. Figure 1). The analysis stage determined the requirements concerning the trustworthy control of CPPS on the basis of four guideline-based interviews with service carriers from the production of various German industrial companies, each lasting one hour and complementary current literature. The interviews were recorded and transcribed to be able to trace the requirements to their source. Afterwards, the paper provides an overview of available technologies, which is based on literature following the method by (Brocke et al. 2009; Levy and Ellis 2006). The design stage results in the technical concept, which was developed using the GAIA method.(Wooldridge et al. 2000) This method was chosen because it specifically focuses aspects of agent modeling.

The main method chosen for the evaluation of the concept is the evaluation through expert reviews. The concept was introduced to an expert in the field of DLT and two experts on data management and industry 4.0 in production systems. The expert in the field of DLT has been conducting research on DLT for over a year. The experts for the practical and production perspective both have many years of experience as CIOs of a medium-sized food manufacturer as well of a leading cooperation in the area of drive and chassis technology. The latter also has the role of an industry 4.0 leader in his company. After the introduction and explanation of the concept, it was discussed with regard to the evaluation criteria relevance, originality and abstraction. The discussions had a duration of one hour each. Again, the discussions were recorded and transcribed afterwards.

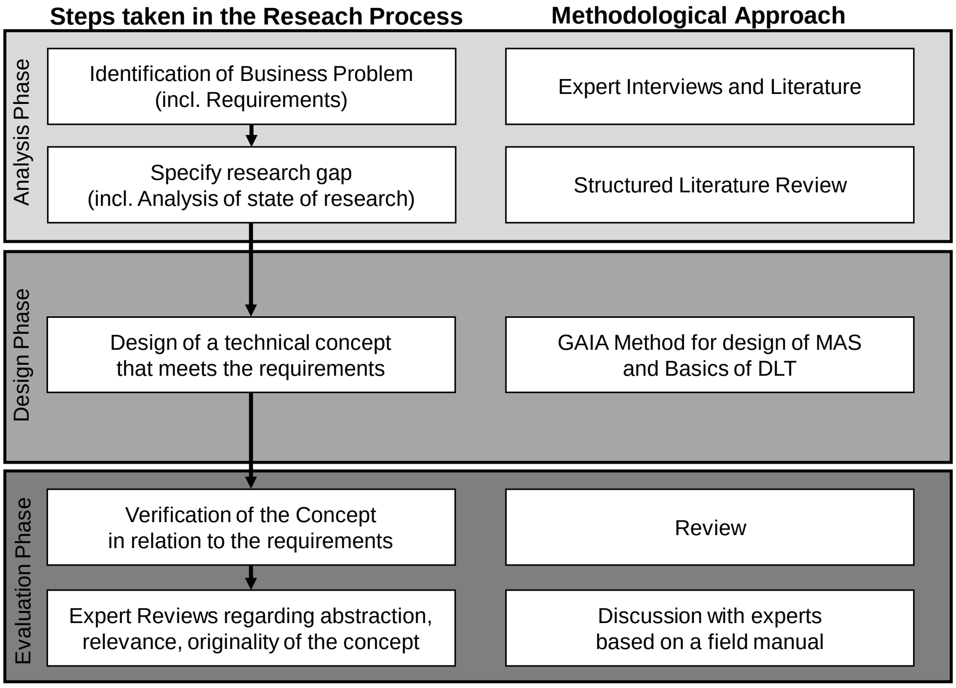

Figure 1. Research Plan

The structure of this paper follows the outlined research process. It is divided according to the stages of the process and the steps within the phases (cf. Figure 1). The focus is on the design phase, which includes the requirements and the concept. The paper concludes with a discussion of the limitations and an outlook and links to possible future research.

Results of the analysis stage

The following section will discuss the changed requirements in regards to data storage and desired behavior of components in a CPPS. Based on these requirements, an assertion concerning the state of technology and research was conducted through examination of the solutions that can be found in the literature.

Requirements

In software and requirements engineering it is common to distinguish between functional and non-functional, quality-of-service requirements.(Pohl and Rupp 2015) Various authors have considered the functional requirements imposed on the production regulation, some in the context of manufacturing execution systems, some in general.(Bedenbender et al. 2017; International Electrotechnical Commission 2013; International Organization for Standardization 2016; Lachenmaier et al. 2015; Verein Deutscher Ingenieure 2016) A list of functional requirements was derived from these sources and double-checked by the experts during the interviews. The functional requirements are therefore not discussed at length in this article. The non-functional requirements are the ones that deal with trustworthiness. They are currently changing due to the introduction of CPPS and are for these two reasons the focus of this article. Based on the conducted expert interviews, and literature that was added to support their cause, this paper considers the following requirements:

1. Flexibility: The concept must reflect the flexibility of cyber-physical production systems and their components. Therefore, dynamically adjustable structures and reactive data handling must be emphasized.(Adolphs et al. 2016)
2. Interoperability: The linking with other systems within a company and the supply chain needs to be promoted.(Tjahjono et al. 2017)
3. Authentication: It must be ensured that an operating entity belongs to the CPPS. Therefore, it is necessary that every entity is uniquely identifiable.(Jänicke et al. 2016)

4. Authorization: When an entity that belongs to the CPPS makes a request it must be ensured that this entity is authorized to do so.
5. Internal consistency: It must be ensured that operating procedures remain unobstructed if changes are made regarding the behavior pattern of a CPPS. In addition, the assignment of an agent to its role must be static and must not be changed.
6. External consistency: During communication between CPPS a uniform consensus about the meaning of utilized data must be agreed upon.
7. Integrity: All data in the CPPS must be verifiable regarding content and temporal correctness at all times. This is important from a legal perspective.(Hornung and Hofmann 2017) Every modification needs to be visible.
8. Protection of communication: All communication within the CPPS must be protected against unintentional participation and modification.(Heer et al. 2017)
9. Reliability: An external attack or a malfunction because of internal problems must not interfere with production.(Schrecker et al. 2016)
10. Performance: The speed of control decisions must be appropriate for the CPPS. A system used for resource allocation operates in the seconds range. Machine control requires real-time processing.

Other requirements, such as functional safety or robustness, that are mentioned in the literature (Adolph et al. 2018; Schrecker et al. 2016) are not addressed here, since they either concern the design of the CPPS components, not the control of production on the shop floor (safety, parts of robustness), or because they are too general and are reflected in other requirements (robustness). Some aspects of robustness can be found in the requirements 9 – Reliability and 1 – Flexibility.

Current state of the Technology and Research and Research Gap

The following section focuses on the current state of technology and research with regard to possible solutions that fulfill the requirements. The analysis looked at the combination of CPPS and MAS, MAS and DLT as well as the combination of DLT and CPPS. Afterwards a literature search for the combination of all three components lead to the research gap. In addition, important terms are defined.

In the past, MAS have frequently been used for the implementation of flexible production systems. More than 20 papers and projects are already known to cover MAS together with CPPS or production regulation systems. This is evident from the analyses in the meta-reviews by multiple authors (Cruz and Vogel-Heuser 2017; Mařík and Lažanský 2007; Monostori et al. 2006; Weiming et al. 2006). The studies show that the application of MAS as a cyber component in CPPS is possible and appropriate. MAS originate in the field of distributed artificial intelligence and deal with so-called software agents.(Jennings 2000) The elements of a MAS are the different software agents that interact with each other. Further elements are an administrative component, which is responsible for the communication process, and a coordination component, which provides the rules and approach to problem resolution (Veit 2003). In this paper the software agent is understood to be the cyber part of a CPPS component (often a machine). The coordination component can be based on a market mechanism with auction-like pricing.(Wooldridge 2009) The combination of MAS and CPPS can therefore be considered state of the technology.

However, agent technology in itself is not yet able to meet all of the requirements above. The coordination within a CPPS entails problems similar to the problems that occur in human negotiations.(Wooldridge 2009) Surveys on connecting CPPS and MAS identified security and trust as one of the few remaining vulnerabilities of existing systems. As the authors of these surveys state, this poses a challenge for research, which has so far only been addressed by workarounds.(Andreadis et al. 2014; Leitão et al. 2016) For example, the Plant Automation based on distribued systems (PABADIS) project used a trusted third party to ensure the integrity of information during the negotiations of agents to generate trust and security.(Peschke et al. 2005) However, this results in a problem regarding the reliability in the event of an attack on a centralized security entity or the problem of who should manage such an entity in an open network of equals. Additionally, these administrators could disguise changes thus affecting transparency and the integrity of the negotiation data. By using DLT, these limitations could be overcome. DLT has successfully been used as an integrated building block in the attempts to solve these problems. An meta review identified 14 papers in which DLT is applied to ensure data integrity and the collaboration or coordination management in MAS (Calvaresi et al. 2018). With regard to the technical concept, DLT thus represents a suitable approach for the challenges of trustworthiness mentioned before. DLT is a continuous digital register duplicated through the participants in a decentralized network.(Burkhardt et al. 2018) Therefore, it allows a transparent and irreversible storage of transactions without the involvement of an intermediary.(Sürmeli et al. 2017) Relevant parts of the DLT are graphs, protocols and smart contracts. The concepts of DLT can be distinguished on the lowest level with respect to their dimensionality. This results in either one- or multidimensional, directed, acyclic graphs (DAG) as a characteristic of DLT. One-dimensional DAGs are called Blockchain. Multidimensional DAG exist in several different forms, for example tangle or hash graph. A protocol, for example Bitcoin, presents an applicable and reusable solution based on the DAG. It is important to mention that currently only a few protocols such as Ethereum support smart contracting. Smart contracts are executable program codes that are no longer modifiable due to redundant storage within the ledger. (Burkhardt et al. 2018)

This paper focuses one-dimensional DAGs, which are also known as blockchains, because they will be part of the concept later. For blockchain, the ledger is achieved by storing transactions in a block. This block is connected to the previous block through a hash value. A transaction describes the transfer of ownership rights. Processing of a transaction takes the following necessary steps (Schlatt et al. 2016):

- One participant starts a transaction, which is sent to all participants in the DL. The participants ("validators") verify the transaction based on consensus.
- Each verified transaction is stored with a hash value or header, Input, Output and a time stamp in one block of the DL
- If the transaction has been verified and has been stored in the blockchain, the transaction is legally binding.

For coordination support, the DLT must be appropriate for MAS as well as CPPS. For this very reason, a literature search was conducted in 2018 on the platform Google Scholar using the search terms 'distributed ledger + CPPS', 'distributed ledger + CPS', 'blockchain + CPPS', and 'blockchain + CPS'. Results of the period from 2015 to 2018 were considered. After reading the abstracts, eleven papers and projects, which focus on the combination of CPPS and DLT were identified and analyzed in detail. This means that using DLT to support cyber-physical production systems is an approach that was considered before in current research projects.

The results gathered regarding the current state of technology showed that the connections of two technologies (the combination of CPPS and DLT, the combination of MAS and DLT as well as the combination of CPPS and MAS) have already been examined in scientific research and have also been applied in production. However, these solutions do not meet all the requirements yet, which leads to a research gap. This is confirmed in the literature on open research topics related to industry 4.0.(Adolph et al. 2018; Anderl et al. 2016) Due to the analyzed papers, a connection of all three elements can be deduced as a possible solution to fulfill the previously mentioned requirements.

Regarding research on DLT, this paper contributes in the areas of business process improvement within industrial firms as well as internet of things applications of Blockchain.(Beck et al. 2017; Risius and Spohrer 2017)

Results of the Design Phase

In the design phase a technical concept that combines MAS and CPPS with DLT is developed as a solution in order to meet the newly emerged requirements. The following paragraphs present the service and acquaintance model as a result of the GAIA method.

Methodical approach in the Design Phase

The following technical concept has been developed using the GAIA method to connect the MAS with the DLT in the CPPS application area. The GAIA method is an agent-based development method that is closely related to object-oriented development methods. The development process is divided into an analysis part and a design part. This breakdown allows the developer to proceed systematically from specific requirements towards a design that is detailed enough to be implemented with traditional software development tools. (Wooldridge et al. 2000) The analysis phase is concerned with the description of how the system works and which interactions occur. The design phase details the cooperation and defines the requirements for individual agents that need to be fulfilled to achieve the goals of the system.

To achieve this, during the analysis part of the GAIA method a role and an interaction model were created and subsequently - during the design part - transferred into an agent, a service and an acquaintance model. Roles and interactions describe the organization of a basic system without technological reference. This is substantiated in the agent, services and acquaintance models, which are more detailed but still on a conceptual level. Again, the focus is on the results from the design phase, since they are more detailed and suited for implementation. During the description of the results, a relation to the matching requirements is established, to increase their traceability.

Role Model and Role Schema

There are three types of software agents in the technical concept, as shown in figure 5: The order agent (OA), the suborder agent (SOA) and finally the resource agent (RA). The agents are deliberative. Furthermore, the internal architecture of the agents is built on the belief-desire-intension (BDI) model (Rao and Georgeff 1995). In addition to the agents there are supporting entities, one of which is the ERP system (ERP) which represents in this case the conventionally centralized parts of a company. The ERP defines the global goals for the entire system, receives customer orders, performs the production planning and after this planning instantiates one order agent for each order. Another supporting entity is the distributed ledger (DL), which serves as product database, agent directory, marketplace and message directory. Moreover, communication is based on a peer-to-peer (P2P) network and not through a client-server network since this is a prerequisite for the use of DLT.

As part of the role model, two roles are illustrated below (cf. Table 1).

Table 1. Role Schema

Role Schema	Order Agent	Resource Agent
Description	Represents an order (e.g. production, maintenance).	Represents a machine on the shop floor (e.g. a multi-axis machining center)
Protocols and Activities	• Asks for product information • Sends status information on order • Negotiates on behalf of the order	• Register resource • Send status information on resource • Bids on production steps • Accepts tasks
Permissions	• Read product information • Write Status • Read/Write Negotiations • Write Suborder Agents	• Read Negotiations • Write status • Write bids • Write machine control
Responsibilities	• Ensures the carry-out of order • Documentation of production processes	• Knows the capabilities of the machine • Ensures the carry out of won negotiations

Interaction Model

The interaction model deals with how the roles interact within a specific protocol. Two sample protocols of a total of 17 protocols are illustrated below (cf. Table 2, Figure 2, Figure 3). The models are notated as activity diagrams in the Unified Modelling Language. A description of how all the protocols work in combination can be found in the section on the service and acquaintance models.

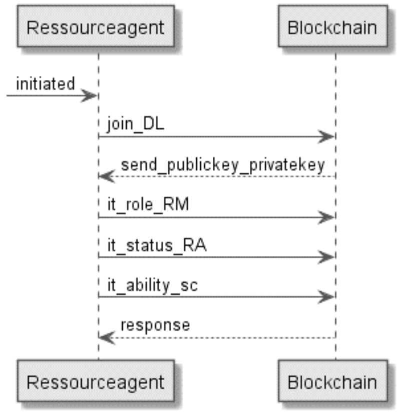

Figure 2. Interactions of Agents in the Protocol P05: register_resource

Table 2. Protocols

Protocol	P05: register_resource	P13: negotiate_resource
Purpose	Registers a resource in the blockchain	In case of unpredicted failures, the RA asks for other resources that can be a substitute for a specific production step
Roles involved	RA, DL	RA, RA(n), DL, SOA
Inputs	• Identification • Capabilities of Resource • Status Resource	• List of suitable resources • Availability of suitable resources
Outputs	Confirmation of Registration	Inform suborder agent of changes regarding the production step
Processing	Cf. Figure 2.	Cf. Figure 3

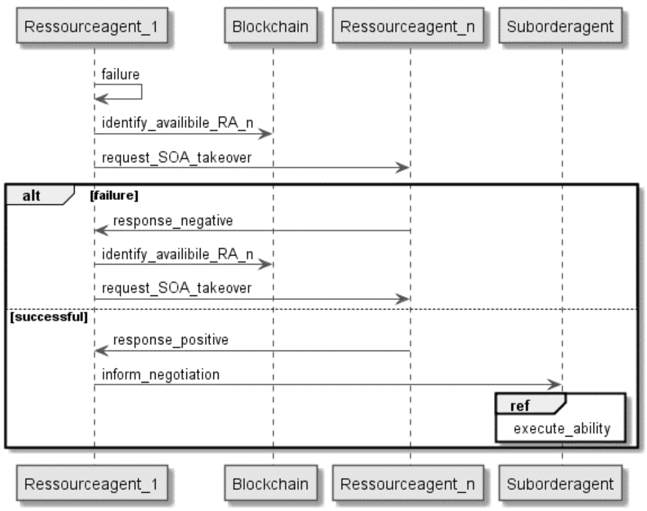

Figure 3. Interactions of Agents in the Protocol P13: negotiate_resource

Agent model

The agent model details the role model of the MAS and describes the types of agents in the systems. The order agent (OA) is responsible for compliance with the production planning rules and goals specified by the ERP. For this purpose, the OA is initialized by the ERP with the necessary order data (order number, delivery date, products). Each OA represents one production order within a facility and receives all necessary data about the product to be manufactured (production steps, tolerances, cost limitations) through querying the DL. During production, it is also responsible for properly updating the order status to facilitate tracking of the order. The OA negotiates with other OAs to ensure global optimization goals are met, thus providing the flexibility needed to make ad-hoc changes to the production schedule. The result of this negotiation is an order priority that is used to determine the production sequence of the products.

The main task of the OA is the management of the CPPS by decomposing an order in independent production steps that can be derived from the product information or work plans (Lachenmaier et al. 2015). For each of those production steps, the OA instantiates a respective SOA. The SOA is responsible for the correct execution of the work stage assigned to it. For this purpose, the agent uses an auction mechanism in connection to DL. Each SOA is assigned to a product instance and uses resources to carry out the its production step.

The shop floor is represented by a number of resource agents (RA). Each machine in production has capabilities that are represented and managed by exactly one RA. The RA is responsible for the utilization of the machines and therefore offers tenders in the DL. Furthermore, it monitors and updates the status of the machine assigned to it. Apart from that, each machine can be individually adapted to the RA and display various standards, as coordination takes place through the respective agent. This ensures the inoperability between different machine manufacturers and standards.

Distributed ledger in the technical concept

The core of this concept demonstrates how agent coordination can be ensured by DLT. This technology is applied in the following multiple times, because DL is used as a product data directory, an agent directory, a message directory, and a marketplace within the concept.

- The product data directory is responsible for the administration of all data that is necessary for the manufacturing of a certain product type. It includes the parts list and the process description, which may be reduced to a set of rules (Lachenmaier et al. 2015).
- The agent directory administers all agents with location, status and if necessary their abilities. This directory ensures a flawless localization and provides an overview and status control of the production system. It also ensures that only verified and truthfully registered resources can bid on the execution of production steps.
- The message directory records all messages that are exchanged in production and thus offers an audit appropriate level of traceability. This ensures the integrity and traceability of decisions in the CPPS.
- The marketplace organizes the production schedule. It receives all requests for the execution of a production step from the SOA and transmits the incoming bids from the RA back to the SOA for execution. By assuming the market role, the DL thus obtains a supporting function with regard to coordination.

To fulfill these roles, all transactions are saved on all entities that are part of the production, which means that a decentralized distributed general ledger (DL) is created. The distributed storage increases the reliability of the system, since failing components can be compensated due to redundancy. External companies can be added to the network as well. This ensures the required interoperability.

Figure 4 shows the extension of the agent architectures of OA, SOA and RA in interaction with the DL. The coordination mechanism draws from the orders that have to be produces, stored in the ERP, as well as the beliefs and intentions of the agents by auctioning production steps to ultimately choose the best bid (cf. Figure 4). Furthermore, the coordination mechanism also interacts with the desire basis to add the results of scheduling as new objectives.

The DL controller is responsible for the interaction between the agent and the DL. The coordination mechanism of the agent interacts with its DL controller in order to receive input, for example offers, as well as to share offers with other agents or to update the status. It allows the agent to coordinate based on the DL. For this purpose, the DL controller provides the functions join_DL and insert_transaction to store and retrieve information on the shared database.

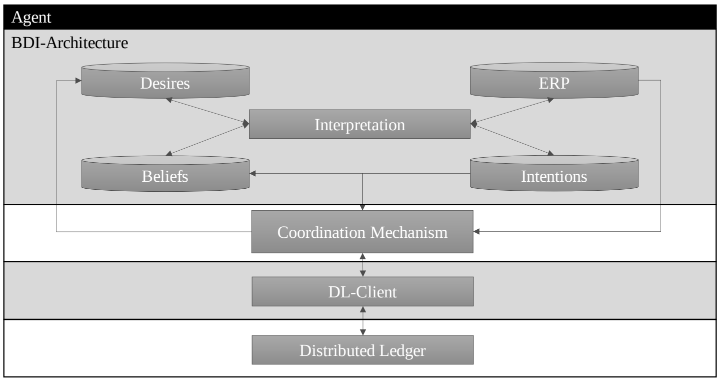

Figure 4. Internal Structure of the Software Agent based on (Basegio et al. 2017)

A public ledger was selected for this paper due to the need to incorporate other companies in the supply chain. However, to access the network a permission is required to guarantee authenticity. This is of great importance because it hinders unauthorized access to the control system and makes all participants known. The ledger design is a so-called consortium blockchain (Xu et al. 2017).

The consortium blockchain uses the practical byzantine fault tolerance (PBFT) protocol as a consensus mechanism. The consensus mechanism, one of the main features of the DLT, ensures that registers that have been distributed to all agents have the same status for all participants. It is also responsible for the consistency and therefore the integrity of the historic data and protects the system of corrupt data sets. PBFT allows for better consistency and latency than other mechanisms (Castro and Liskov 2002). However, it is not suited for a large number of nodes because all participants of a network must approve the verification of a block. For this, all nodes need to be known, which is only the case in permission-based blockchains. With PBFT, all participants in the network cast their vote on the correctness of a message. The prerequisite for this mechanism to work is that no more than one third of the agents in the control system are faulty. A transaction can only be executed when two thirds of the network participants approve of it. This fulfills the requirements of consistency. Thus, the main advantage of PBFT as opposed to other mechanisms is that a transaction possesses one hundred percent of the finality immediately after the release (Zheng et al. 2017). This is a necessary requirement for a CPPS because once a control decision has been made, it can only be reversed at considerable resource costs. Moreover, PBFT allows for a greater throughput of transactions. The disadvantage of this mechanism is that all participants of a network must be known in advance, which is made possible by using a consortium blockchain.

The services and acquaintance model

The activities used to control the production system as well as the flow of production are described in the following paragraph. The model focuses on the technical perspective of the course of action. The focus of the technical concept is to illustrate the support functions of the DLT. Therefore, special attention is paid to the protocols with a connection to the blockchain. The execution of these protocols corresponds to transactions within the blockchain. These transactions always consist of an identifier, input, output and a time stamp. The services and acquaintance model shows how the agents communicate based on the protocols they use.

Starting the system, the product types of the ERP are registered in the network using protocol P07 and the OA is initiated with P01, as shown in Figure 5 in connection to table 3. Afterwards, each agent must register at the blockchain using the protocols P03, P05 and P12 when it is initiated. All previously mentioned protocols use the function “join_DL” of the DL client. This command assigns a public and private key to each agent or product type for digital signing. Each described protocol whose participant is the DL needs to be digitally signed to ensure the unambiguous traceability and authentication. The function “insert_transaction” is used during registration to enrich the identifier of the respective agent or product type with specific data. Thus, the product types register with P07 in the DL with their bill of materials and process description or feature list from the ERP. Through the use of P03, the OA adds the manufacturing priority, which is determined by P09 for the assignment represented by the OA, and its assigned SOAs. Furthermore, the SOA uses P12 to write the processing step, which has been transferred to it. The description of the processing step consists of the parts and the description of the production step, which are previously determined by the OA through the use of the P08 and transmitted to the SOA through P10 at its generation. A processing request is then put up for auction. At this time, the orders are prioritized by assigning a maximum payable amount to them, which reflects the order priority set by the OA. The RAs adds the capabilities they provide to the DL by calling P05. It should be noted that its capabilities are implemented as smart contracts to ensure proper execution by the machine according to the rules that apply for the specific step of production (such as tolerances). The RAs receive information about the advertised requests through its DL client and can thereupon submit their bids in relation to their current status and workload targets.

The condition of the agents is updated through its DL client by the creation of new transactions as soon as the auction has been won, which provide a conclusion about the beliefs of the agent. This is done through the execution of P14 or the function “insert_transaction”. This way, the current workload of the agents and resources is documented.

Table 3. Protocols

No.	Protocol	No.	Protocol
P01	initiate_OA	P10	initiate_SOA
P02	change_OA	P11	change_SOA
P03	register_order	P12	register_SOA
P04	update_status_order	P13	negotiate_ressource
P05	register_ressource	P14	bid_task
P06	update_status_ressource	P15	execute_ability
P07	register_producttype	P16	terminate
P08	request_producttype	P17	request_status
P09	negotiate_order		

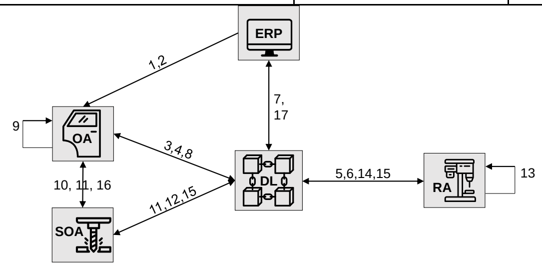

Figure 5. Services and Acquaintance Model

The pricing is based on the model of the machine cost rate calculation with the help of the ERP, as well as the belief and the intention basis of the RAs. The offers describe the amount an SOA would need to pay for processing at the respective machine. Furthermore, the RAs are offered the opportunity to coordinate their offers with each other by means of P13. To simplify matters, it is assumed that all offers are submitted at the same time. Once again, the blockchain is responsible for the synchronization of the bids. The respective DL clients of the SOAs update their perception in reference to the bids. The SOAs are now able to decide, which bid is the best as well as which RA should handle the processing. For this technical concept it is determined that the lowest priced offer is the best offer, however the capabilities of a resource or the duration of the production step might be considered as well. The goal of CPPS is therefore to minimize the processing cost, thus ensuring the efficiency of the overall system. The capabilities of the RAs are implemented as smart contracts, as previously mentioned. It is therefore possible that the capabilities are executed after the selection process through the respective SOA using

P15. One component of the contract is the payment of the RA by the SOA. Each SOA is provided a certain amount of crypto currency by the corresponding OA. The OA in turn acquired the cryptocurrency from the ERP at its initialization.

When the smart contract is executed, all other RAs that submitted offers for this request are informed that they did not win the bid. The result of the allocation is subsequently submitted to the belief and desire basis of the participating agents to guarantee an autonomous optimization of the allocation process. Additionally, the OA monitors the transactions of its respective SOAs and updates its order status depending on the processing status of the SOAs with P04. If a SOA completed a smart contract, it is terminated by its associated OA using P16. The remaining crypto assets of the SOAs are thereby transferred to the superordinate OA. If these OAs leave the production, their surplus returns to the ERP. The currency cycle is closed when the RA leave the amount of currency they earned to the ERP which forwards it to the next OA. Thus, this technical concept is a closed ecosystem.

By querying the order status from the ERP using P17, the system's ability to provide information to the customer is ensured at all times. During the production process, changes can be made in the shape of machine malfunctions or as short-term order changes. If a machine fails due to a malfunction, the status of the RA in the blockchain is updated using P06. This ensures the properties of flexibility and reliability of the whole system. The information reaches the ERP through the previously described process and reacts in the form of a maintenance order. This maintenance order is treated in the same way as a production order. However, an auction is not necessary because the task description specifies that only the machine that requires maintenance can process the order. In the event of an order change with short-term notice, the ERP updates the responsible OA by using P02. The P02 determines if the change is feasible by checking of the completion status. If the production step has not been completed before, the corresponding SOA affected by the change is updated through P11. This links to the requirement of reliability. If a processing step is already advertised on the DL, but not yet allocated, the SOA can update the request with the new parameters by using P11 (cf. Figure 5 and Table 3).

Results of the evaluation phase

The authors verified the concept in relation to the requirements and made sure that the requirements are met. The link between concept and requirements is mentioned in the respective models of the concept. As the main part of the evaluation, an expert review was conducted as recommended in the memorandum on design-oriented information systems. (Osterle et al. 2010) The experts reviewed the concept regarding its originality, relevance, and abstraction from both the perspective of DLT and production.

Abstraction

The review of the experts determined that the degree of abstraction of the technical concept is appropriate and the requirements are met. Furthermore, the technical concept is not tailored to a specific company or industry. The experts therefore regard the transferability of the conception to their production environments as feasible. However, there is no generic technical concept that covers the entirety of production requirements. It is therefore important to evaluate which specific changes are appropriate for the production in the respective company.

Relevance

The experts consider decentralized autonomous control systems as trend-setting and challenging because of the increasing complexity of CPPS. The technical concept provides a possible solution approach for safeguarding such systems. The concept proves especially useful in companies that want to implement DLT in production. The system integrator of a company, for example, can benefit from the technical concept by receiving a bundled, clearly defined overview.

However, this also reveals the limitations of the concept because the concept must be further specified to be ready for implementation in production. For practical use, the concept should be expanded, particularly with regard to production-related areas such as logistics or the handling of production resources and tools. In the opinion of experts, the concept offers the necessary interfaces and starting points to achieve a targeted continuation of the technical concept through to implementation.

Originality

According to the knowledge of the experts, DLT had not yet been associated with agent-based CPPS by the time this paper was written. The originality of this paper is therefore confirmed by experts. Additionally, the originality of this technical concept is supported by the fact that two parts of the paper, the DLT which only recently emerged as well as the viewpoint of CPPS, already represent areas with a high degree of innovation.

Conclusion, Limitations and Outlook

The developed technical concept shows that an auction-like market mechanism, which supports the coordination within an agent-based production regulation, is made possible through DLT, which then supports the coordination of agents in the CPPS and ensures trustworthiness at the same time. A blockchain structure with PBFT consensus mechanism is recommended as a variant of the DLT. The advantages of using DLT in a CPPS are traceability, immutability and reliability of the control data. Although the decision-making speed of the technical concept is reduced in favor of these characteristics, the concept offers practical benefits. The recommended course of action for decision-makers in manufacturing companies with regard to production control is for new production control systems to potentially be developed to implement a CPPS in order to meet the new requirements. The presented technical concept points out a possible solution on the basis of agent technology in connection with the advantages of the use of DLT and is therefore an example for the potentials of DLT.(Tapscott 2016)

The concept is limited in its scope as it is intended for discrete manufacturing scenarios. Also, the empirical foundation of interviewed experts is not large enough for generalization. This has been partially compensated for by the addition of relevant literature that supports the requirements. The objectivity and reliability of the research are improved by the documentation of the interviews and of the concept according to good practices, such as the GAIA method, UML and use of field manuals.

The paper and its evaluation part demonstrate that there is potential for DLT solutions in the area of production. The GAIA method that is intended for the development of multi agent systems can also be applied to develop systems that involve DLT. The concept is generic and can therefore serve as a blueprint to further adapt to the specific requirements of individual businesses.

In order to give a final recommendation, however, the developed technical concept requires a pilot implementation to support the conceptionally demonstrated advantages. Therefore, the next step in future research should be a real-world evaluation of the concept.

References

Abbas, B. 2017. *Verteilte Multi-Agenten Zur Planung Und Steuerung Von Produktionsumgebungen Auf Basis Der Gewaltenteilung Und Gewaltenverschränkung*. Aachen: Apprimus.

Adamczyk, H., Angeli, C., Böttinger, K., Filipovic, B., Fritsche, W., Houdeau, D., Hutle, M., Jänicke, L., Jochem, M., Kisch, M., Klasen, W., Kosch, B., Krammel, M., Linke, L., Nitschke, T., Rohr, S., Sandner, M., Schmitt, M., Schwibach, M., Sinner, N., Teuscher, A., Walloschke, T., and Zorenc, J. 2016. *It Security in Industrie 4.0: Action Fields for Operators*. Berlin: Federal Ministry for Economic Affairs and Energy (BMWi).

Adolph, L., Ammon, E., Bausch, U., Beck, S., Bedenbender, H., Bentkus, A., Billmann, M., Braunmandl, A., Brumby, L., Börkircher, M., Clasen, M., Meer, J. d., Diedrich, C., Dirzus, D., Elmasn, F., Epple, U., Focke, G., Fliehe, M., Franchi, N., Friedrich, J., Fritz, J., Gayko, J., Gerhardt, H.-U., Graus, M., Hagedorn, J., Hauck, A., Heidel, R., Hörcher, G., Jeske, T., Jännicke, L., Kirchhoff, B., Klasen, W., Klemm, E., Köpp, T., Kötter, W., Krug, C., Leboucher, Y., Lemke, M., Löwen, U., Lutsch, C., Meister, G., Mehrfeld, J., Metzger, T., Meurer, D., Meyer, O., Middelkamp, S., Mosch, C., Rannenberg, K., Rauchhaupt, L., Rehm, G., Reischle-Schedler, G., Rolle, I., Sagert, S., Schmidt, J., Steiger, G., Stock, P., Tausch, A., Tenhagen, D., Uslar, M., Wei, W., and Wischmann, S. 2018. *German Standardization Roadmap*, (Version 3 ed.). Berlin, Frankfurt: DIN e.V. and DKE Deutsche Kommission Elektrotechnik.

Adolphs, P., Berlik, S., Dorst, W., Friedrich, J., Gericke, C., Hankel, M., Heidel, R., Hoffmeister, M., Mosch, C., Pichler, R., Rauschecker, U., Schulz, T., Schweichhart, K., Steffens, E. J., Taube, M., Weber, I., Wollschlaeger, M., and Mätzler, S. 2016. *Reference Architecture Model Industrie 4.0 (Rami4.0): Din Spec 91345*. Berlin: Beuth.

Anderl, R., Bauer, K., Bauernhansl, T., Berlik, S., Broy, M., Diegner, B., Diemer, J., Fay, A., Gausemeier, J., Goericke, D., Grotepass, J., Hilger, C., Hornung, G., Jasperneite, J., Kalhoff, J., Kubach, U., Lanza, G., Löwen, U., Menges, G., Meyer-Kahlen, J.-P., Michels, J. S., Nebel, W., Reinhart, G., Ripperda, C., Rödig, H., Schmidt, F., Stiedl, T., Hompel, M. t., and Zeidler, C. 2016. *Forschungsagenda Industrie 4.0: Aktualisierung Des Forschungsbedarfs*. Berlin: Bundesministerium für Wirtschaft und Energie (BMWi).

Andreadis, G., Klazoglou, P., Niotaki, K., and Bouzakis, K.-D. 2014. "Classification and Review of Multi-Agents Systems in the Manufacturing Section," *Procedia Engineering* (69), pp. 282-290.

Badr, I. 2011. *Agent-Based Dynamic Scheduling for Flexible Manufacturing Systems*. Stuttgart: Shaker.

Basegio, T. L., Michelin, R. A., Zorzo, A. F., and Bordini, R. H. 2017. "A Decentralised Approach to Task Allocation Using Blockchain," *International Workshop on Engineering Multi-Agent Systems - EMAS*, Cham: Springer International Publishing, pp. 75-91.

Beck, R., Avital, M., Rossi, M., and Thatcher, J. B. 2017. "Blockchain Technology in Business and Information Systems Research," *Business & Information Systems Engineering* (59:6), pp. 381-384.

Bedenbender, H., Bentkus, A., Epple, U., Hadlich, T., Heidel, R., Hillermeier, O., Hoffmeister, M., Huhle, H., Kiele-Dunsche, M., Koziolek, H., Lohmann, S., Mendes, M., Neidig, J., Palm, F., Pollmeier, S., Rauscher, B., Schewe, F., Waser, B., Weber, I., and Wollschlaeger, M. 2017. *Industrie 4.0 Plug-and-Produce for Adaptable Factories: Example Use Case Definition, Models, and Implementation*. Berlin: Federal Ministry for Economic Affairs and Energy (BMWi)

Böttinger, K., Filipovic, B., Hutle, M., and Rohr, S. 2016. *Industrie 4.0 Security Guidelines: Recommendations for Actions*. Frankfurt am Main: VDMA.

Brettel, M., Friederichsen, N., Keller, M., and Rosenberg, M. 2014. "How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective," *World Academy of Science, Engineering and Technology* (85), pp. 37 - 44.

Brocke, J. v., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., and Cleven, A. 2009. "Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process," *ECIS*, pp. 2206-2217.

Burkhardt, D., Werling, M., and Lasi, H. 2018. "Distributed Ledger," *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, pp. 1-9.

Calvaresi, D., Dubovitskaya, A., Calbimonte, J. P., Taveter, K., and Schumacher, M. 2018. "Multi-Agent Systems and Blockchain: Results from a Systematic Literature Review," Cham: Springer International Publishing, pp. 110-126.

Castro, M., and Liskov, B. 2002. "Practical Byzantine Fault Tolerance and Proactive Recovery " *Journal of ACM Transactions on Computer Systems (TOCS)* (20:4), pp. 398-461.

Cruz, S. L. A., and Vogel-Heuser, B. 2017. "Comparison of Agent Oriented Software Methodologies to Apply in Cyber Physical Production Systems," *2017 IEEE 15th International Conference on Industrial Informatics (INDIN)*, pp. 65-71.

Duisberg, A., Haas, P., Hullen, N., Kriesel, T., Kroke, T., Schweinoch, M., and Wittek, N. 2018. *Blockchain Und Recht Im Kontext Von Industrie 4.0*. Berlin: Bundesministerium für Wirtschaft und Energie (BMWi).

Haas, M. 2018. *Deutscher Industrie 4.0 Index 2018*. Köngen: Staufen.AG.

Heer, T., Heintel, M., Jänicke, L., Jochem, M., Kärcher, B., Kisch, M., Mehrfeld, J., Oeynhausen, G., Pfeiffer, T., Schewe, F., Schmitt, M., Schulz, D., Tenhagen, D., Theuerkauf, K., Teuscher, A., and Walloschke, T. 2017. *Sichere Kommunikation Für Industrie 4.0*. Berlin: Bundesministerium für Wirtschaft und Energie (BMWi).

Hevner, A. R., March, S. T., Park, J., and Ram, S. 2004. "Design Science in Information Systems Research," *MIS Quarterly* (28:1), pp. 75-105.

Hornung, G., and Hofmann, K. 2017. *Industrie 4.0 Und Das Recht: Drei Zentrale Herausforderungen* München: acatech – Deutsche Akademie der Technikwissenschaften.

International Electrotechnical Commission. 2013. "Iec 62264-1: Enterprise-Control System Integration – Part 1: Models and Terminology." Berlin: Beuth.

International Organization for Standardization. 2016. "Iso 18828-2: Industrial Automation Systems and Integration — Standardized Procedures for Production Systems Engineering — Part 2: Reference Process for Seamless Production Planning."

Jänicke, L., Jochem, M., Kaiser, H., Klasen, W., Klimke, M., Kosch, B., Linke, L., Mehrfeld, J., Nitschke, T., Sandner, M., Stoltz, M., Walloschke, T., and Zimmermann, S. 2016. *Technical Overview: Secure Identities*. Berlin: Federal Ministry for Economic Affairs and Energy (BMWi).

Jennings, N. R. 2000. "On Agent-Based Software Engineering," *Artificial Intelligence* (117:2), pp. 277-296.

Kagermann, H., Wahlster, W., and Helbig, J. 2013. *Recommendations for Implementing the Strategic Initiative Industrie 4.0*. acatech – National Academy of Science and Engineering.

Lachenmaier, J., Lasi, H., and Kemper, H.-G. 2015. "Entwicklung Und Evaluation Eines Informationsversorgungskonzepts Für Die Prozess- Und Produktionsplanung Im Kontext Von Industrie 4.0," in: *Wirtschaftsinformatik*. pp. 1-15.

Lee, E. A., and Seshia, S. A. 2017. *Introduction to Embedded Systems: A Cyber-Physical Systems Approach*, (2nd ed.). Cambridge: MIT Press.

Leitão, P., Karnouskos, S., Ribeiro, L., Lee, J., Strasser, T., and Colombo, A. W. 2016. "Smart Agents in Industrial Cyber–Physical Systems," *Proceedings of the IEEE* (104:5), pp. 1086-1101.

Levy, Y., and Ellis, T. J. 2006. "A Systems Approach to Conduct an Effective Literature Review in Support of Information Systems Research," *InformingSciJ*), pp. 181-212.

Mařík, V., and Lažanský, J. 2007. "Industrial Applications of Agent Technologies," *Control Engineering Practice* (15:11), pp. 1364-1380.

Monostori, L., Váncza, J., and Kumara, S. R. T. 2006. "Agent-Based Systems for Manufacturing," *CIRP Annals* (55:2), pp. 697-720.

Osterle, H., Becker, J., Frank, U., Hess, T., Karagiannis, D., Krcmar, H., Loos, P., Mertens, P., Oberweis, A., and Sinz, E. J. 2010. "Memorandum on Design-Oriented Information Systems Research," *European Journal of Information Systems* (20:1), pp. 7-10.

Pantförder, D., Mayer, F., Diedrich, C., Göhner, P., Weyrich, M., and Vogel-Heuser, B. 2017. "Agentenbasierte Dynamische Rekonfiguration Von Vernetzten Intelligenten Produktionsanlagen: Evolution Statt Revolution," in *Handbuch Industrie 4.0 Bd.2*, B. Vogel-Heuser, T. Bauernhansl and M. ten Hompel (eds.). Berlin, Heidelberg: Springer, pp. 31-44.

Peschke, J., Luder, A., and Kuhnle, H. 2005. "The Pabadis'promise Architecture - a New Approach for Flexible Manufacturing Systems," in: *10th IEEE Conference on Emerging Technologies and Factory Automation*. pp. 491–496.

Pohl, K., and Rupp, C. 2015. *Requirements Engineering Fundamentals* Santa Barbara: Rocky Nook.

Rao, A. S., and Georgeff, M. P. 1995. "Bdi Agents: From Theory to Practice," *The First International Conference on Multi-Agent Systems (ICMAS-95)*, pp. 312-319.

Risius, M., and Spohrer, K. 2017. "A Blockchain Research Framework," *Business & Information Systems Engineering* (59:6), pp. 385-409.

Schlatt, V., Schweizer, A., Urbach, N., and Fridgen, G. 2016. *Blockchain: Grundlagen, Anwendungen Und Potenziale*. Bayreuth: Projektgruppe Wirtschaftsinformatik des Fraunhofer-Instituts für Angewandte Informationstechnik FIT.

Schrecker, S., Soroush, H., Molina, J., LeBlanc, J., Hirsch, F., Buchheit, M., Ginter, A., Martin, R., Banavara, H., Eswarahally, S., Raman, K., King, A., Zhang, Q. C., MacKay, P., and Witten, B. 2016. *Industrial Internet of Things Volume G4: Security Framework* Industrial Internet Consortium.

Sürmeli, J., Der, U., Jähnichen, S., and Vogelsang, A. 2017. "Ein Rahmenwerk Zur Protokollierung Von Transaktionen in Distributed Ledgers," *Informatik-Spektrum* (40:6), pp. 595-601.

Tapscott, D. 2016. *Blockchain Revolution: How the Technology Behind Bitcoin Is Changing Money, Business and the World*, (International edition ed.). New York: Portfolio / Penguin.

Tjahjono, B., Esplugues, C., Ares, E., and Pelaez, G. 2017. "What Does Industry 4.0 Mean to Supply Chain?," *Procedia Manufacturing* (13), pp. 1175-1182.

Veit, D. J. 2003. *Matchmaking in Electronic Markets: An Agent-Based Approach Towards Matchmaking in Electronic Negotiations*. Berlin Heidelberg: Springer.

Verein Deutscher Ingenieure. 2016. "Vdi 5600 - Part 1 - Manufacturing Execution Systems." Berlin: Beuth.

Weiming, S., Lihui, W., and Qi, H. 2006. "Agent-Based Distributed Manufacturing Process Planning and Scheduling: A State-of-the-Art Survey," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* (36:4), pp. 563-577.

Wooldridge, M. 2009. *An Introduction to Multiagent Systems*, (2nd Ed. ed.). Chichester: Wiley.

Wooldridge, M., Jennings, N. R., and Kinny, D. 2000. "The Gaia Methodology for Agent-Oriented Analysis and Design," *Autonomous Agents and Multi-Agent Systems* (3:3), pp. 285-312.

Xu, X., Weber, I., Staples, M., Zhu, L., Bosch, J., Bass, L., Pautasso, C., and Rimba, P. 2017. "A Taxonomy of Blockchain-Based Systems for Architecture Design," *2017 IEEE International Conference on Software Architecture (ICSA)*, pp. 243-252.

Zheng, Z., Xie, S., Dai, H., Chen, X., and Wang, H. 2017. "An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends," *2017 IEEE International Congress on Big Data (BigData Congress)*, pp. 557-564.