A Decentralized Marketplace for Collaborative Manufacturing

Adrian Hofmann  
*University of Würzburg*, adrian.hofmann@uni-wuerzburg.de

Chiara Freichel  
*University of Würzburg*, chiara.freichel@uni-wuerzburg.de

Axel Winkelmann  
*University of Würzburg*, axel.winkelmann@uni-wuerzburg.de

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A DECENTRALIZED MARKETPLACE FOR COLLABORATIVE MANUFACTURING

Research Paper

Adrian Hofmann, University of Würzburg, Würzburg, Germany, adrian.hofmann@uni-wuerzburg.de
Chiara Freichel, University of Würzburg, Würzburg, Germany, chiara.freichel@uni-wuerzburg.de
Axel Winkelmann, University of Würzburg, Würzburg, Germany, axel.winkelmann@uni-wuerzburg.de

Abstract

The manufacturing industry requires intra- and inter-organizational collaboration to cope with increasing cost pressure, high market dynamics, and sophisticated customer requirements. Therefore, many solutions emerged in recent years that enable the sharing or trading of production capacities in different industries. These solutions are based on a centralized platform. The business model of those platforms introduces transaction costs for users. Additionally, these platforms often create lasting dependencies, lack transparency, and therefore trust. At the same time, new technologies such as blockchain emerged, which promise to solve these various issues by enabling decentralized transactions. This paper uses a design science research approach to develop an infrastructure for decentralized collaborative manufacturing. Therefore, we matched requirements for existing platform approaches to decentralizing technologies. To evaluate the approach, we conducted expert interviews to verify the usefulness and assess potential improvements to extend existing research dimensions of collaboration systems.

Keywords: Decentralized Marketplace, Manufacturing Capacities, Blockchain, Sharing Economy, Token Economy
1 Introduction

Uncertainty arising from future demand or machine availability poses significant challenges to production planning and can result in overcapacity or capacity shortages. Both cases decrease profitability by either excess cost or lost sales. Simultaneously, modern manufacturing is becoming more digitized and enables new types of collaboration, such as intra- and inter-organizational sharing of production capacities. The concept of connecting manufacturing capacities between companies is not new. However, in recent years research moved from production networks (Wiendahl and Lutz, 2002) to platform models for collaborative manufacturing. Schmitt et al. (2015) introduced a marketplace concept to enable inter-organizational sharing of production capacities. The sharing economy’s overall concept has since proven to become more relevant in business-to-business environments (Ocicka and Wieteska, 2017).

These platforms often take the form of centralized marketplaces. However, centralized platforms often suffer from trust issues (Hawlitschek et al., 2016; Nofer et al., 2017). Especially when detailed information about a company’s production capabilities and its economic situation has to be shared with a third party. Additionally, solutions for niche production technologies or small production networks are not available since the low market volume does not provide a viable business case for centralized providers. Finally, the involvement of an intermediary can introduce additional cost for each transaction.

Blockchain technology has been driven by the vision to eliminate these intermediaries (Nakamoto, 2008). Accordingly, numerous proposals have been suggested to use the technology in electronic markets (Alt, 2020; Noll and Alt, 2020; Notheisen, Hawlitschek, and Weinhardt, 2017; Richter, Mangelkamp, and Weinhardt, 2018; Zhang and L. Wang, 2017). The concept of blockchain-based markets has opened a new area of research (see Section 2). The markets can be either operated on large public networks or in a small consortium. However, most market approaches inherit the property of complete transparency from the underlying blockchain architecture. Since some users are unwilling to share information about their production capacities with a third party, they are unlikely to share this information on a transparent public ledger.

Against this backdrop, we seek to incorporate other trusted decentralized computation paradigms into a marketplace solution. In recent years, zero-knowledge proofs, specifically, zk-SNARKs (Pinto, 2020) and secure multiparty computation (Zhong et al., 2020), have shown significant synergy effects with blockchain technology. With these technologies, information can be kept private while still being used to match supply and demand on a decentralized platform efficiently. Therefore, our research focuses on the blockchain market perspective infrastructure for electronic markets proposed by Alt (Alt, 2020), by developing a new decentralized marketplace model without an intermediary. To develop the new infrastructure, we set the following research questions:

RQ1: Which technologies can be used to solve trust issues in collaborative manufacturing?
RQ2: How should an infrastructure for a decentralized marketplace for production capacities be designed?

We applied a design science research (DSR) approach to develop the novel infrastructure to answer the research questions. The rest of this paper is structured as follows: In Section 2 we provide an overview of related literature and previous work on decentralized marketplaces, followed by a description of the methodology for developing and evaluating the artifact in Section 3. The proposed infrastructure is introduced in Section 4. It consists of a description of the three architectural layers and a sequence model describing the actors’ interaction on the marketplace and the layers. Section 5 summarizes the results of the expert interviews to explore the artifact’s performance in its real environment. The final section discusses the results and concludes this paper.
2 Foundations and Related Work

Our paper tackles topics from the three areas: digital markets and platforms, production networks, and distributed ledger technology. In the following, we present previous research that combined at least two of these areas, as shown in Figure 1. Out of these combinations, we identified the areas’ intersections from literature: 1. production capacity sharing, 2. decentralized marketplaces, and 3. supply network blockchains. We will describe the related literature in the order shown in Figure 1. Finally, we discuss the approaches that combine all areas as well as the research gap.

1. Production Capacity Sharing

Driven by the sharing economy, production resources can be shared within a network of manufacturing companies using a centralized platform. Therefore, supply and demand can be balanced on the market by efficiently allocating resources.

2. Decentralized Marketplaces

Most widespread approaches of decentralized marketplaces focus on trading energy, financial assets, and data. These markets allow direct peer-to-peer trading within communities, e.g., trading of cryptocurrencies, gold, stocks or securities in the finance sector. Data to be traded can be managed by smart contracts and reaches from IoT data to personal health or genomic data.

3. Supply Network Blockchains

By representing products through digital twins, blockchain realizes transparency in complex supply chains by eliminating intermediaries. Additionally, tracking and tracing of goods is accompanied by a decentralized record of all material movements.

Figure 1. Areas of Related Literature and Research Gap

Research on production capacity sharing combines the areas of digital markets and production networks. Mainly driven by the sharing economy trend, the idea of a capacity marketplace for sharing production resources emerged (Schmitt et al., 2015). Within an integrated network of manufacturing companies and inter-organizational production planning, machines can be higher utilized, and supply and demand can be balanced on the market (Freichel et al., 2019; Schmitt et al., 2015). Most approaches propose to realize the marketplace by using a centralized platform to distribute manufacturing capacities. While there are concepts for sharing agricultural machines and woodworking equipment (Daum and Birner, 2020), we focus on stationary machines that cannot easily be moved to a different manufacturing facility. Freitag, Becker, and Duffie (2015) modeled and simulated different sharing mechanisms in production networks. Specifically, in additive manufacturing, Stein, Flath, and Walter (2019) developed a market mechanism that efficiently allocates resources utilizing stochastic optimization. This process can further be automated by allowing an automated matching of products with additive manufacturing machines. Several approaches pursue the development of decentralized marketplaces. The first and most widespread approaches focus on the energy sector. The decentralized market approach is adaptable in this context since electricity is an extremely homogenous good (Kirpes et al., 2019). Additionally, electricity generation becomes more decentralized if households produce their own power. Furthermore, total transparency is not an issue in this market. The overall trend towards local energy markets allows local communities to direct peer-to-peer energy trading without relying on large energy exchanges (Mengelkamp et al., 2018;
However, even large energy exchanges, like the European Energy Exchange, have discovered the potential of decentralized markets and assessed the benefits of a blockchain-based market (Alt, 2020). The next trend in decentralized markets can be summarized with the term decentralized finance (DeFi). While DeFi spans other areas such as decentralized lending, DeFi is mostly concerned with decentralized trading of various assets, most notably cryptocurrencies (Zhang and L. Wang, 2017). However, the underlying technologies allow trading of other assets that can be represented as tokens such as gold, stocks, or securities (Notheisen, Willrich, et al., 2019). The final large area is decentralized data trading platforms. Trading data on decentralized marketplaces can be very efficient since the access to the data can be managed by blockchain smart contracts (Noll and Alt, 2020). The data traded on these platforms reaches from internet of things (IoT) data to personal health or genomic data (Jin et al., 2019; J. Xu et al., 2019). Apart from these more extensive areas, numerous articles exist on other industries, where a decentralized market, with its added transparency and disintermediation, offers advantages over a centralized solution. For example, Zavolokina, Miscione, and Schwabe (2020) presented a marketplace for used cars. Finally, Notheisen, Hawlitschek, and Weinhardt (2017) presented a market engineering approach for blockchain-based markets. We used this approach as an orientation for our market design.

The research on blockchain applications in supply chains and supply networks mainly focuses on increasing transparency in complex supply chains. The main focus is on enabling traceability of goods along the supply chain to their source (Kurpjuweit et al., 2021). Due to the immutability and disintermediation, the blockchain contains a decentralized record of all material movements (Banerjee, 2018). The two most common use cases control perishable goods and prevent illegal sourcing of natural resources, especially in the pharmaceutical and food industry (Bocek et al., 2017; Qinghua Lu and Xiwei Xu, 2017). With a similar concept, blockchain helps prevent counterfeit products’ circulation in the post supply chain. Each product is represented by a digital twin on the blockchain that gets transferred when the products’ ownership changes (Toyoda et al., 2017). The disintermediation of information is another significant application domain for blockchains, especially in cross-country supply chains (Hull, 2017). The technology is used for cross-border payments (Guo and Liang, 2016), business-to-government information sharing (Engelenburg, Janssen, and Klievink, 2019), and automation of business processes with smart contracts (Weber et al., 2016). For a more detailed overview of blockchain technology application in supply chains, we refer to the comprehensive literature review by Y. Wang, Han, and Beynon-Davies (2019).

We could only identify one project that combines all three areas. The Decentralized Industry Marketplace is developed by the IOTA Foundation (Sobolev and Schneider, 2019) and is designed to enable machine data exchange, similar to Noll and Alt (2020). However, the functionality is focused on industry environments. Unlike our approach, the marketplace is not designed to trade production capacities. Therefore, this paper encompasses all areas shown in Figure 1 to develop a decentralized marketplace for collaborative manufacturing.

3 Methodology

In the following section, we describe the methodology we used to develop the decentralized marketplace infrastructure. We use a design science approach to guide the development and evaluation of the artifact. As we seek to solve a practical problem, we follow the guidelines proposed by Hevner et al. (2004). Additionally, we follow the DSR process, according to Peffers et al. (2007). Finally, blockchain-specific approaches exist to guide the development of blockchain applications (Wust and Gervais, 2018; X. Xu, Weber, et al., 2017; X. Xu, Pautasso, et al., 2016). We extend the technologies used by other decentralized, trustless mechanisms, such as zero-knowledge proofs and secure multiparty computation, as proposed by Hofmann (2020).
3.1 Development of the Artifact

The framework shown in Figure 2 guides our methodological procedure, according to Hevner et al. (2004). The authors propose that the artifact has to fulfill the environment’s business needs to ensure relevance. The artifact is designed to connect producing companies of various sizes. Especially small and medium enterprises (SME) suffer more from fluctuations in demand, and a marketplace for production capacities can help them become more flexible and robust towards these fluctuations (Freitag, Becker, and Duffie, 2015; Stein, Flath, and Walter, 2019). We assume that the companies use information systems to plan their production and that they can be extended to purchase or sell production capacities automatically. If this is not the case, the proposed solution can still work but offers slightly less utility. Some steps must be performed manually, especially transferring data about physical machines to the blockchain-based assets. Furthermore, the artifact must be based on existing theories, models, and methodologies to ensure scientific rigor. We base our approach on existing models, methods, and instantiations of decentralized systems, especially marketplaces (see Section 2). We use the design process by Peffers et al. (2007) and methodologies for qualitative interviews to ensure methodological rigor.

To ensure a high utility of the developed artifact, we applied the following seven guidelines for the application of DSR introduced by Hevner et al. (2004).

**Design as an artifact:** The research result is a proof-of-concept infrastructure for a decentralized marketplace for production capacities. The design allows users to buy and sell production capacities without revealing their capacities to third parties.

**Problem relevance:** The designed mechanisms allows connecting supply and demand in a decentralized ecosystem. Additionally, it eliminates previous decentralized approaches’ main weakness, namely the transparency of purely blockchain-based approaches.

**Design evaluation:** We use semi-structured expert interviews to evaluate the proposed solution’s utility, usefulness, and practicability. We further describe the evaluation methodology in Section 3.2.

**Research contribution:** We extend the knowledge base by introducing an approach to represent manufacturing capacities with fungible tokens that can be traded with existing technologies. By constructing a complete infrastructure, we build the foundation for the implementations of fully decentralized and secure marketplaces.

**Research Rigor:** To ensure scientific rigor, we take DSR frameworks as well as blockchain-based frameworks into account in the design process. Additionally, we base our research on prior scholarly publications focused on decentralized marketplaces and disintermediation.
Design as a research process: To find a solution that fits the problem, we use the iterative process proposed by Peffers et al. (2007). We evaluate existing concepts and solutions from the scientific literature to build a preliminary infrastructure during this process. Additionally, we use an ex-ante evaluation to incorporate requirements from practitioners and refine the infrastructure.

Communications of research: We describe the infrastructure and the interactions necessary to exchange capacities on the marketplace. During the evaluation, we secondarily focused on making the description of the solution understandable for practitioners and scholars to maximize the range of the contribution.

3.2 Evaluation of the Artifact

Following the definitions of Venable, Pries-Heje, and Baskerville (2016), we perform a formative evaluation in-between ex-ante and ex-post evaluation. We employed the evaluation with qualitative expert interviews to explore our artifact’s performance in its real environment (Venable, Pries-Heje, and Baskerville, 2016). We rely on an exploratory research approach by integrating multiple stakeholders’ perceptions with extensive experience in the domain of interest. In the following paragraphs, we describe the selection of interview partners, the semi-structured questionnaires’ design, and the procedures for data collection and analysis. The interviewees all have knowledge about platform business models as well as blockchain technologies. We use criteria such as market position, experience in the research field, and industry and company size for the selection. The final set of interviewees consists of three blockchain experts of different companies (experts A, B, and C). A short overview of the interviewees is displayed in Table 3.2.

Even though the group consists of practitioners, all experts have a research background and are currently involved in blockchain research projects. This small panel of highly specialized experts was suitable to quickly improve the model within this first evaluation. We plan technical evaluations with an implemented marketplace prototype and a broader evaluation with potential users. However, this is out of the scope of this conceptual work.

<table>
<thead>
<tr>
<th>Experts</th>
<th>Industry</th>
<th>Position in Company</th>
<th># Employees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert A</td>
<td>Software Development</td>
<td>Scientist in Residence</td>
<td>300</td>
</tr>
<tr>
<td>Expert B</td>
<td>Blockchain Development and Consulting</td>
<td>Product Manager</td>
<td>70</td>
</tr>
<tr>
<td>Expert C</td>
<td>Software Development</td>
<td>Business Development Manager</td>
<td>100</td>
</tr>
</tbody>
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Table 1. Classification of Interviewees

We designed semi-structured questionnaires as interview guidelines with questions that can all be answered openly. We provide the opportunity to include emerging concepts and ideas (Edwards and Holland, 2013; Paré, 2004). Besides essential, factual, or direct questions that address this study’s key topic, structuring questions were used to guide the interview progress. The questionnaire starts with a preamble explaining the goals and scope of this study. The preamble is followed by general questions asking for advantages and disadvantages of central marketplaces to prepare the interviewees for the following, more complex questions about decentralized marketplaces. The following two parts of the questionnaire include descriptions of the developed layer model and sequence model for decentralized capacity exchange and questions concerning the models’ understandability. In the last section, we investigate the minimum requirements and exclusion criteria for using the marketplace. Finally, we ask for issues with the proposed design and improvement potential for these issues. To ensure appropriate clarity, structure, and length of the questionnaire, we conducted a pilot study with two independent researchers (Berg, 2001). We did only apply minor changes to the final questionnaire. The interviews were conducted by phone and documented as audio recordings. For data analysis, we applied the process suggested by Kuckartz (2018) and Green et al. (2007). We transcribed the recordings literally, adapted the sentence structure, deleted filling words, and anonymized the final transcript. In the next step, we coded the transcripts by keywords to aggregate relevant information. We analyzed the frequency of specific keywords and their synonyms to determine relevant codes with sub-codes. Finally, we grouped the codes into higher-level categories. For
each category and code, we collected all text segments to aggregate and compared relevant statements. After this process, the coded information was used to evaluate and improve our artifact, described in the following section.

4 Infrastructure for Decentralized Collaborative Manufacturing

In the following section, we introduce the proposed infrastructure. First, we describe the overall architectural model and its layers and components. Then, we explain buying and selling capacities on the marketplace and the interaction between the layers. In both subsections, we directly integrated our findings gained from the evaluation.

4.1 Architectural Model

We use a three-layer model in Figure 3, consisting of a (1) machine layer, (2) token layer, and (3) matching layer. First, on the machine layer, the real-world machines of type are represented. Free capacities of these machines correspond to a number of capacity tokens on the token layer. For example, one capacity token represents one hour of machine time. Additionally, value tokens on the token layer are used to pay for capacities. These value tokens could be a stablecoin initially (e.g., the value of one token corresponds to one dollar) but could later be freely tradable if used in a stable ecosystem.

The underlying token technology should use privacy-preserving features such as zero-knowledge proofs or ring signature algorithms to hide transaction inputs and outputs to mitigate transparency issues (Hopwood et al., 2020; Noether, Mackenzie, and Research Lab, 2016). To enable trading of capacities for value tokens, buyers and sellers must submit their orders to the decentralized order book. Buyers of capacities order capacities in the form of capacity tokens for a maximum price of value tokens. In contrast, sellers order a minimum amount of value tokens for their amount of capacity tokens. Additionally, both buyers and sellers must submit a deadline until which the offer must be processed. Finally, within the matching layer, both sides’ offers are matched to maximize the revenue on the platform. In the following, we further explain each layer in detail.

4.1.1 Machine Layer

The machine layer represents the physical/actual machines that are present at each manufacturing company. The machines are indexed by type, and machines of each type are enumerated. A manufacturer can have multiple machines that are all the same type of CNC machine (M_{1,1}, M_{1,2}, ...), and several different models of additive manufacturing machines (M_{2,1}, M_{3,1}, ...). For example, in additive manufacturing, different models can utilize different techniques to manufacture and bond layers or differ in the maximum build dimensions. These differences influence the type of goods produced on the machine and the cost to produce it. Additionally, it can be important to differentiate between individual machines, as individual machines of a model can have different characteristics despite the same manufacturing process, such as the material that is being processed. We assume that each machine type has a finite production capacity allocated by a production planning system.

4.1.2 Token Layer

The token layer is connected to the machine layer, as each type of machine has a corresponding token on the token layer. As previously stated, each token represents, e.g., one hour of free capacity on a given machine. The concept of tokenization of real-world assets is well established and lays the foundation of the so-called token economy (Lee, 2019). Since capacity is mutually interchangeable, the capacity tokens should be representable as a fungible token. To prevent one user from holding all capacity tokens of one kind, we propose not to limit the tokens’ supply. On the technical side, this can be achieved with a token based on the ERC20 token standard with variable supply (Vogelsteller and Buterin, 2015). If suppliers
want to hide their transaction history of sold capacities, they can choose to use a new wallet address for each time they sell tokens on the marketplace. However, sellers of capacities can also use the same address as a marketing device to show their positive record.

We propose an approach to issue different tokens for each combination of machine, material, and certifications. This would not change the matching process than only associating tokens with machine types, but only the number of different tokens. A higher granularity allows better differentiation between the different offers resulting in different pricing for each token. We show examples, how different tokens for these combinations would correspond to ERC20 tokens in Figure 4.

Figure 4. Each Combination of Machine, Material and Certification Corresponds to a Unique Token

Figure 5 shows how the user choices would translate to an order that can be transacted to the matching layer. This process can be automated if the capacities and resources, such as materials, are planned with an information system. If the planning is done manually, choosing the correct token to sell or buy is also a manual process and complicates this step.

The degree of differentiation of the tokens is highly dependent on the underlying manufacturing process.
We are, therefore, looking forward to implementing a prototype in different manufacturing scenarios to validate the approach further.

To allow trading the capacity tokens against money, we introduce a second type of tokens, the value tokens. From a technological perspective, we recommend a privacy-preserving token technology as seen in cryptocurrencies such as Zcash or Monero (Pinto, 2020; Zhong et al., 2020). This is important to minimize transparency on market activities and hide sensitive information about sales from other participants. On the economic side, it should be chosen whether the token should be priced according to the market or if it should be a so-called stablecoin (Mita et al., 2019). This means that the token’s value is pegged to a national currency, through active monetary policy, introducing an intermediary who actively regulates the price. However, the intermediary would not have any insights into the individual transaction behavior or production capacities. Additionally, if the motivation to introduce a decentralized marketplace is the small market size, this intermediary would not interfere with the objectives of the marketplace.

The token layer can be implemented directly on a blockchain. The proposed solution is designed for manufacturers who do not want to share information about their capacities with a centralized third party or for smaller production networks to make centralized solutions available or affordable. For the first scenario, the blockchain can be either completely public or powered by a consortium blockchain operated by a few larger stakeholders. The solution of a consortium blockchain is also suitable for the second scenario. Here, all stakeholders should operate the network. This network architecture allows for much more efficient consensus algorithms and a much lower cost for operating the network compared to a public network (Hofmann, 2020). This consensus can eliminate many of the inefficiencies that are often associated with blockchain technology.

### 4.1.3 Matching Layer

The matching layer provides the primary mechanism behind the proposed marketplace design. We rely on a dark pool protocol to enable automatic pricing, such as described by Zhang and L. Wang (2017). The protocol allows the trade of arbitrary crypto-assets, like cryptocurrencies (value tokens) and ERC20 tokens (capacity tokens), and is, therefore, ideal for our use case.

Trades are placed on a decentralized, hidden order book and are matched through a distributed matching engine. The order matching works like a centralized exchange based on the bid and ask prices for the capacities. The matching engine uses multiparty computation, which provides order execution without exposing sensitive information such as price and volume at a particular position. This prevents other market participants from taking advantage of the transparency of an open order book by methods such as frontrunning (Zhang and L. Wang, 2017).

For the matching, orders are split up into fragments transmitted to different nodes in the network. The fragments are not a fraction of the orders’ value, but a separation of sensitive data of the underlying order. Each node performs order matching computations on fragments of different orders. The result is combined with the result of other nodes that computed different fragments.

This protocol does not run directly on the blockchain as a smart contract. Instead, it additionally requires the operation of the decentralized dark pools. The participants of the network can operate these nodes.
Since the protocol relies on a trusted party, such as a blockchain, we propose to run it alongside the blockchain nodes. This matching process has three advantages compared to other, purely blockchain-based approaches (Zhang and L. Wang, 2017). First, the full order can only be reconstructed if over half of the fragments are combined, making the network resistant against order reconstruction attacks. Second, since only half of the fragments are required, the network is also resilient to denial-of-service attacks and nodes’ failures during the computations. Finally, not all nodes have to perform all computations to perform a secure matching. Performing expensive computations securely outside of the main blockchain network and only proving the results to the blockchain is an excellent way to improve the scalability of blockchain applications (Hofmann, 2020).

4.2 Process Model

Figure 6 shows the complete process for buying and selling capacities using a UML sequence diagram. The three layers and the buyer and seller are the entities represented at the top of the diagram. Rectangles represent times in which an entity is performing an operation. The sequence of operations is performed from top to bottom. Arrows represent messages that are triggered by the entities. If the arrows are dashed, the message is a response to a previous message.

To buy manufacturing capacities, the buyer must own value tokens to exchange on the marketplace. These tokens can be bought via the token layer as a first step. Then the offer can be placed on the matching layer. The seller must first check how much capacity is still available on different machines. For the capacity to be sold on the marketplace, the seller must request capacity tokens for the respective machine. These capacity tokens can then be offered on the matching layer. The matching layer matches offers in real-time and, if two offers can be matched, automatically swaps the corresponding tokens on the token layer. This token swap ensures that the seller can not offer the same capacity again on the token layer. The only possibility to accidentally double book the sold capacity would be for the seller to sell the capacity on a different platform.

As soon as the buyer receives the capacity tokens, the production information must be sent to the seller, who can then start manufacturing the ordered items. The information can be encrypted with the public key of the token sender to protect the content from unauthorized access (Menezes et al., 1996). As soon as the goods are manufactured, they are shipped to the buyer, verifying that the order is complete and meets the quality criteria. Finally, the seller of the capacities can sell the value tokens via the token layer to exchange them for fiat currency.

![Sequence Model for Decentralized Capacity Exchange](Figure 6)
5 Evaluation Results

During the evaluation, Expert A stated that the quality of products, even if produced on the same type of machine, can differ dramatically. Therefore, the expert proposed to include meta-information about the machine in the tokens. Expert B suggested solving this issue by incorporating information about the processed material and manufacturers’ certifications into the tokens. Since this is not trivial for the proposed type of tokens and it is hard to consider this information in the matching process, we propose an approach to issue different tokens for each combination of machine, material, and certifications. We further discussed this idea with expert B, who stated that this idea only works if the choice of the correct token to buy and sell is automated, based on the users’ choices of machines, material, and certifications. Expert C confirmed that companies would not adopt a marketplace that is too complicated to use. We demonstrated that it is not difficult to associate capacities with tokens. However, this can only work fully automated if the artifact can directly be integrated into a production planning system.

Concerning the value tokens, expert A argued that the marketplace could only be successful if it is not subject to speculation. Using a stablecoin would minimize the risk of using the value token as a speculative asset.

All experts stated that information leaks in the matching process and network failures are the main exclusion criteria that would prevent users from joining the marketplace. The properties of the chosen protocol, therefore, fit the requirements of the experts.

Expert C criticized that the process does not include a mechanism to modify or cancel an order once it is matched. Since all transactions are unchangeable after they are committed to the blockchain on the token layer, this could lead to fraud in the marketplace. Attackers could offer capacities on the marketplace that are not available and immediately sell the value tokens after the token swap. Both could be mitigated by introducing an escrow smart contract into the process. Asgaonkar and Krishnamachari (2019) introduced such a mechanism, specifically to enable cheat-proof delivery and payment of goods. However, including this in our proposed marketplace is out of this paper’s scope and subject for future research. The idea behind such a smart contract is that the tokens are not swapped immediately to the buyers’ and sellers’ wallet but are locked into a smart contract and can only be released if both parties agree to it, i.e. that the real world transaction produced goods were produced and met the buyers’ quality criteria. If the two parties cannot agree, the case has to be disputed internally, or legal measures must be taken.

Finally, all experts stated that fraudulent behavior or insufficient product quality could be prevented if only trusted companies could join the marketplace. This could either be achieved by using a consortium blockchain and establish a precise legal setting. Alternatively, a public blockchain can be used with decentralized governance and a decentralized know-your-customer solution, such as proposed by Parra-Moyano, Thoroddsen, and Ross (2019).

6 Conclusion

The presented concept of a marketplace for manufacturing capacities allows companies to use the advantages of sharing economy since modern manufacturing is becoming more digitized and enables new types of collaboration. Intra- and inter-organizational sharing of capacities within a production network allows buyers of capacities meeting demand and sellers to utilize available and unused capacities. First approaches have been proven successful and realize this concept as centralized marketplaces. However, we could identify trust issues and transaction costs as the main limitation.

Against this drawback, we identified blockchain technology as a suitable solution since it eliminates intermediaries, keeps information private if combined with new cryptographic technologies, and is successfully used in comparable electronic markets scenarios. Therefore, we could answer our first research question of which technology we could use to solve trust issues in collaborative manufacturing. To answer our second research question, we applied the DSR approach to design an infrastructure for a decentralized marketplace for production capacities consisting of two models. The three-layer model
describes the interaction of the machine layer, token layer, and matching layer. The complete process of decentralized capacity exchange between buyer and seller is designed as a sequence model. The presented infrastructure combines well-established concepts from blockchain technology with new cryptographic primitives to enable secure and private trading. Hereby, capacities are represented by ERC20 tokens with variable supply that can be traded against a stablecoin on a decentralized exchange. The capacity tokens can represent complex combinations of machines, materials, and certifications to allow users to specify their orders precisely.

This research provides a scientific as well as practical contribution. From a scientific point of view, it contributes to the emerging research on sharing production capacities. The research complements existing articles on an infrastructure perspective and, thus, expands the concept of a marketplace for production capacities on new design elements. Second, our results contribute to general, practical research on digital markets. With the theoretically grounded design science approach, the study can contribute to a more precise elaboration of blockchain use cases. Especially on an abstract level, the proposed infrastructure could be used for other mutually interchangeable goods.

However, our research is not without limitations and leaves room for future research. We are aware that the blockchain technology introduces a complex solution to simple problems. While there is a research stream that searches for solutions to this complex problem, we argue that at the current state, the proposed marketplace is not ready to be implemented in practical environments. However, we view the proposed architecture as a reference for future implementations.

As this study is exploratory, the final artifact design is influenced by the chosen methods and the derived implications. Since we evaluated our artifact with blockchain experts between ex-ante and ex-post, we will add an ex-post summative evaluation with blockchain experts as well as potential users in further research. Especially the evaluation with potential users will show how well the representation of capacities with tokens is suited for their use case, since it only takes time into account, not material consumption or wear and tear of the tools. Moreover, our evaluation showed further improvement potential, such as the inclusion of escrow smart contracts to secure the marketplace against fraud.

Nevertheless, the artifact design provides a basis for future research tackling concrete implementation in a real-world inter-organizational production network applying the concept of a decentralized marketplace for sharing manufacturing capacities in practice.

Acknowledgement

This work has been developed in the projects "PIMKoWe" and "Individualisierung Digital". "PIMKoWe" (reference number: 02P17D160) is partly funded by the German Ministry of Education and Research (BMBF) within the research program "Industrie 4.0 – Kollaborationen in dynamischen Wertschöpfungs-netzwerken (InKoWe)" and managed by the Project Management Agency Karlsruhe (PTKA). "Individualisierung Digital" is partially funded by the European Union through the European Regional Development Fund (ERDF). The authors are responsible for the content of this publication.

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*Twenty-Ninth European Conference on Information Systems (ECIS 2021), A Virtual AIS Conference*


