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Development and Evaluation of a Blockchain Concept for Production Planning and Control in the Semiconductor Industry

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Abstract – Blockchain technology promises several benefits for operations management, but reported use cases, concepts and applications are rare. This contribution indicates the findings from a case study of analyzing the suitability of blockchain technology for semiconductor manufacturing at the 300 mm wafer frontend facility of Infineon Technologies in Dresden, Germany. This plant contains one of the most highly automated fabrication lines in the industry. Here, several different and isolated digital software tools are used to control manufacturing, all accessing centralized databases with different views and restrictions. We assess if and how a blockchain solution could and should be designed to enhance the analytic capabilities for this facility using the design science approach and evaluate the economic value of the designed application using the analytical hierarchy process.

Keywords – Blockchain technology, semiconductor manufacturing, operations management, case study

I. INTRODUCTION

Operations management (OM) has seen several technologies disrupting the industry in light of Industry 4.0 [1]. One of the technologies with the potential for a substantial disruption in OM, manufacturing, and supply chain management (SCM) is blockchain technology, a technology based on decentralization, transparency, and visibility [2]–[4]. Blockchain can be perceived as a trustless system since no entity has to rely on the trustworthiness of a specific counterpart. The technology itself verifies confidence in the network with immutable transaction records and decentralized governance [2], [3]. After first use cases in the finance industry, recently, some concepts followed in SCM, but the area of OM and manufacturing has not been considered in-depth to date [5]. Although the prospective potentials are recognized throughout the industry, there are few publications or reports on the successful application of the technology [6].

Especially manufacturing companies need to redefine their strategic objectives and goals in the current industrial revolution. It is essential to look beyond the hype surrounding new technologies and identify the real potential of these technologies within the context of Industry 4.0. In this contribution, we focus on one of the most complex and digitalized industries: semiconductor manufacturing. To follow the More-than-Moore approach, semiconductor manufacturers invest heavily in automation as well as productivity improvements and are at the forefront of virtual production control using sensors and IoT technologies [7]. However, there are several issues

related to the manufacturing process in a frontend wafer factory (fab), including volatile, high product mixes and volumes, complex process flows, and limited capacity of expensive equipment [8]. To analyze the suitability of blockchain technology for semiconductor manufacturing, we conduct a case study at the 300 mm wafer fab of Infineon Technologies in Dresden, Germany. Several different digital software tools have been implemented at the production control departments of the wafer fab over the past years, all of which access centralized databases with different views and restrictions. We explore the idea of applying blockchain as a decentralized alternative in semiconductor production control using the design science approach (based on Hevner et al. [9]) and evaluate the economic value of the designed application using the analytical hierarchy process.

This contribution aims to answer two research questions regarding the application of blockchain technology for operations management, especially in the semiconductor industry and considering the specific use case of the case company:

RQ1: How can semiconductor manufacturing profit from new digital technologies for the storage, analysis and visualization of production data? Would a blockchain solution be suitable?

RQ2: How should a blockchain application be structured for a suitable use case in semiconductor manufacturing and how will it perform compared with conventional database technologies?

The remainder of this contribution is structured as follows. In Section 2, we present the research methodology, followed by a collection of the results in each process step in Section 3. Findings are presented and discussed in Section 4 and a conclusion will be drawn in Section 5.

II. METHODOLOGY

To analyze whether blockchain technology could be a viable solution for the semiconductor industry, we conducted a case study at the 300 mm wafer fab of Infineon Technologies in Dresden, Germany. The design science research (DSR) approach by Hevner et al. [9] was adapted for the case study. This method, which originates from information systems research, aims to increase the efficiency of the organization in the center of the research project where interfaces between the human workforce, organization, and technology occur.

The resulting three-pillar research framework is shown in Fig. 1. In this case study, the environment consisted of organization and technology and was assessed in multiple interviews with experts from different departments. Analyzing the environment provides insight into the current status of the research problem regarding people, processes, technologies, infrastructure, strategies, and applications. A knowledge base accumulation – using the existing literature on blockchain technology – serves as the theoretical foundation for the new solution. Finally, the knowledge base is applied to the specific environment to develop a novel technological solution for the research problem. This novel solution will then be evaluated by employing the analytic hierarchy process based on Saaty [10]. This application environment serves as a first example in order to collect experience with the use of blockchain technology. With the new understanding of the possibilities of blockchain and its current development status, the case company can pursue more complex projects, where blockchain will bring even more benefits.

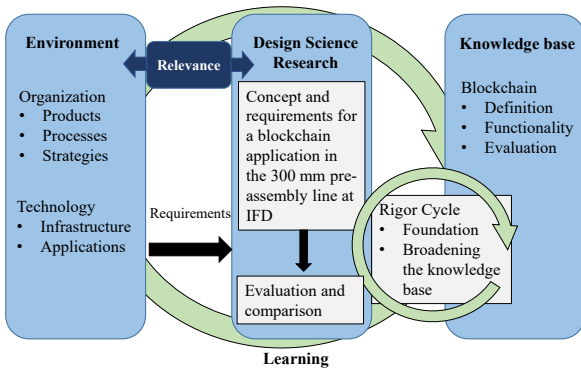


Fig. 1. Adapted DSR framework (based on Hevner et al. [9])

III. RESULTS

A. Environment – 300 mm semiconductor manufacturing

By analyzing the manufacturing processes and supporting IT systems in our case study, three main issues were identified: varying, high product mixes, complex process flows, and customer orders competing for limited capacities. These three issues combined create irregular phases of overload and underload of the equipment in the fab, even stronger fluctuation in the utilization of the individual process flows and a significant amount of insecurity in production, staff, and maintenance planning. The fluctuations in the production process result in significant potential unused. Maintenance measures and staff deployment could be improved and machine utilization increased. A simulation based on real-time data from upstream processing steps of the lots would allow for an adjustment of the downstream areas, like the pre-assembly area in the focus of this case study. The pre-assembly area of the 300 mm fab is highly dependent on the upstream areas and usually receives information on incoming WIP at very short notice, if at all. Data security is an important issue since some of the lots are exchanged between different factories in the supply chain and the data

must be transferred consistently for this purpose. Furthermore, as different segments in the production pursue their own KPIs and act with a strong self-interest, values in the databases change frequently and lead to constant rescheduling. Therefore, the different production divisions can also be considered as independent entities to a certain extent making information sharing an even more critical issue.

Several analytical systems are available to the planners and engineers to cope with this situation and prepare for future overload or underload scenarios. However, all of these systems (e.g., process flow visualization, standard reporting, fab KPIs) access a centralized database, called the data warehouse, which contains static, historical production data and therefore serves the purpose of overall equipment effectiveness management (OEE). Current analysis tools are only available on a static basis and cannot provide all the data in real-time. For the semiconductor environment with all its complexities, the operating curve management (OCM) approach is more fitting than OEE. OCM takes into account dynamic information and real-time data and allows to consider volatile conditions in the planning process. An important step towards implementing this OCM approach is to provide high-quality data with optimal availability and reliability. A new data storage and data collection technology to accomplish this goal will benefit the data provision and exchange for better strategic, tactical, and operational decisions.

B. Knowledge base – blockchain technology

Blockchain was identified as one possible technology to help achieve this goal. The blockchain represents a distributed ledger that is stored decentrally as a single record of data in blocks. The communication occurs among distributed (and often geographically dispersed) nodes in a peer-to-peer network through transactions and elements of cryptography, replicating the immutable ledger between all participants in the network. Organizations of all kinds can communicate and exchange data securely with other organizations they do not need to trust, without having to use an intermediary. For a detailed technical description, we would like to refer the reader to recent contributions and systematic literature reviews on blockchain technology, e.g., [4], [11], [12]. Blockchain technology can be used in different forms, e.g., in a public, private, or consortium configuration. Besides, the feature of smart contracts is probably the most inspiring for applications in OM and SCM. A smart contract represents a computerized transaction protocol that can automatically execute the terms of a specified contract, once the terms are met. Apart from the automation potential and means to increase efficiency by using smart contracts, other properties of blockchain applications like immutability, transparency, and disintermediation can be highlighted [11], [12]. Through these technical features, blockchain as a decentralized data storage technology can provide a higher level of reliability, transparency, flexibility, irreversibility, and integrity than a conventional centralized database while also eliminating costs for networking, transparency,

trust, and monitoring. However, as there is no central supervising entity in the network, several issues like authority, vulnerability, privacy, legal implications, computing and data storage capacities, connectivity, and scalability have to be considered for each specific use case.

Recent reviews only accumulated limited numbers of scientific papers on blockchain applications in SCM and OM [4], [6]. Reports on successful proofs-of-concept or applications that are productively used in OM in the industry are scarce. Regulatory uncertainty, missing standardization, or intellectual property concerns are the main barriers for adoption [13], [14]. Some authors contributed with a technical perspective on manufacturing applications, e.g. [5], [15], [16]. Industry initiatives can be highlighted too, e.g., startups like Everledger dealing with tracking and tracing solutions for worthy products to ensure the declared provenance [17]. IBM and Maersk are developing solutions to digitalize global trade activities in a project called TradeLens [18]. Industry surveys indicated that OM is perceived as one of the most promising areas for blockchain adoption by industry [19], [20]. Supplier contract management, digital threat mitigation, as well as production and maintenance tracking, are some opportunities that manufacturers would like to pursue in future applications. However, the majority of companies actively involved in blockchain projects still deal with accounting or financial applications only [21]. Lack of awareness is an issue, as many professionals consider the technology as too complex to understand and apply.

Several authors ask for empirical evidence on implementation challenges and efficient measures for implementation in case studies [11], [12]. Additionally, blockchain technology should be compared with other technologies for the digital transformation of OM, SCM, and manufacturing, always keeping in mind the economic value of the technology.

C. Development of a blockchain solution

The usability assessment, according to Dieterich [22], was utilized to assess a specific use case that we developed from the input of multiple expert interviews and discussions. The concept is based on a blockchain that tracks the individual transactions in all manufacturing operations completed on an individual lot. With the existing systems, this aggregation of data can only be created for individual lots and with considerable effort. Out of several concepts, the blockchain concept was estimated

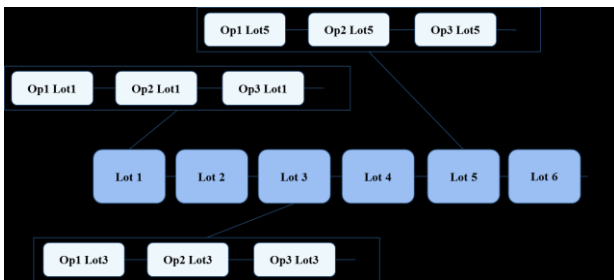


Fig. 2. Structure of the blockchain concept for the manufacturing facility

to have the highest potential to improve data provision and exchange for planning purposes. In the blockchain network, an individual blockchain will be created for each lot to track the status and completion of operations. This enables a timely pre-planning of the pre-assembly on a reliable data basis. The individual blockchains could be joined together in a universal blockchain, as depicted in Fig. 2.

Once the general transaction flow is determined, the next decision involves the type of the network. Due to confidential manufacturing data, a public and permissionless network is not suitable for our concept. As only internal supply chain partners are collaborating and exchanging data via the blockchain at the moment, we opted for a private blockchain network. This could be adapted to a consortium blockchain easily, once more partners are added to the network in future operations.

An open-source platform was chosen as the foundation for this application. The Hyperledger project coordinated by the Linux Foundation has designed blockchain frameworks for different network scenarios. Many experts have joined the project community to optimize the solutions and broaden the framework portfolio in order to establish blockchain in the service and manufacturing industry. A very active community provides development support for blockchain solutions through forums, tools, and tutorials and aims at the establishment of industry standards. Hyperledger Fabric was chosen for the presented use case because of its suitability for application in the manufacturing industry [23].

Hyperledger Fabric consists of the blockchain itself and a so-called world state. The blockchain irreversibly tracks the transactions that change the status of the data set and lead to the current status. The world state stores only the current status of the system, but no transaction history, thus making the process of calculating the data status after a new transaction more efficient. The smart contract – the program code a new transaction is based on – can directly access this current status without having to calculate it from the transaction history stored in the blockchain. The world state will change after each transaction and is not irreversible. The unique lot number is used as the key for this data set and the value contains all relevant lot data (e.g., last production step, product type, route, customer, cycle time).

The blockchain now stores blocks that contain the transactions of the individual manufacturing operations. In addition to the transaction data, a block contains several pieces of metadata (block number, a hash string of the transaction data, timestamp, etc.) and is linked to the previous block by stating the hash string of the previous block. Fig. 3 shows how a transaction is processed in Hyperledger Fabric. A decentralized app connects the end-user (machine or human operator) to the blockchain. It formulates data input for the blockchain network and contacts the peer or group of peers that must confirm the transaction before it can be added to the blockchain.

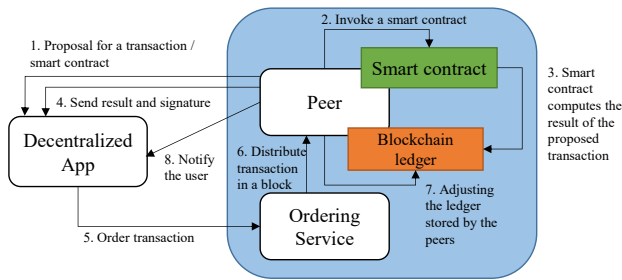


Fig. 3. Process flow in Hyperledger Fabric [23]

This peer invokes a smart contract and calculates the resulting data set. If this can be done correctly, the peer informs the app that the transaction may be published. Then, the app contacts the ordering service, which is responsible for forming blocks and publishing them to all peers in the network. As soon as a peer receives a new block from the ordering service, its copy of the blockchain ledger will be updated. Each participant needs to set up the decentralized app and specify the smart contracts for the business processes that should be supported by the blockchain. A simplified smart contract for a query of lot data and a new transaction is shown in the following. Lines 2 and 5 represent the data input that the decentralized app transfers to the peer.

```

1  lot contract:
2  query (lot);
3  get (lot);
4  return (lot);
5  update (lot, Operation, TransactionType, ...):
6  get (lot);
7  lot.operation = Operation;
...
29 lot.route = Route;
30 put (lot);
31 return lot;

```

D. Evaluation of the blockchain solution

A qualitative analytic hierarchy process (AHP) was used to evaluate the economic value of the new blockchain concept. The potential of blockchain as a useful data storage technology was compared with the potential of centralized database solutions currently established at the case company. For this purpose, a decision hierarchy was

designed based on common decision problems of Industry 4.0 and digital technologies, indicated in Fig. 4.

Three main categories were identified for the analytical hierarchy process to evaluate the concept (based on [10]), including technical, organizational, and economic criteria. The weights of the criteria were determined in several discussions with internal and external experts of the semiconductor fab at Infineon Dresden. Economic criteria are considered most important (54%), followed by technical criteria (34%). Organizational criteria are considered less important for this decision problem (12%) because an organization in this innovative industry can quickly adapt to changing circumstances. The blockchain solution was compared with the current solutions present in the case company, which are different software tools connected to central databases. Interestingly, blockchain is not predominant regarding technical criteria but outperforms on data security, completeness, and fault tolerance. Nevertheless, the other main categories were dominated by blockchain. Overall, the blockchain outperformed the data warehouse with a score of 0,64 vs. 0,36. Especially the transparency, secure communication, customizability, standardization of data, strategic fit, and knowledge gains were praised by the experts. The full survey details, the AHP structure and results are provided in the Appendix, which is accessible at [24] due to limited space available.

IV. DISCUSSION

The results can be used to answer the two research questions: The design process of the blockchain solution indicated that blockchain could also be suitable for internal supply chain applications in semiconductor manufacturing. In many cases, there are similar constellations in internal production segments as between business partners, e.g., self-interest as well as lack of transparency and data continuity. Here, blockchain can offer an approach to move from centralized solutions to a simple form of data transparency. The irreversibility is an essential element. Besides, in advanced applications, the reimbursement using cryptocurrencies could be used for efficient payment processing. The choice of network type is of great importance. Many concepts and solutions for B2B are currently only conceivable in a private or consortium

Decision category	Weighting	Block-chain	Data warehouse	Decision category	Weighting	Block-chain	Data warehouse	Decision category	Weighting	Block-chain	Data warehouse
Technical Criteria	0,34	0,49	0,51	Organizational Criteria	0,12	0,65	0,35	Economic Criteria	0,54	0,74	0,26
Feasibility	0,23	0,20	0,80	Transparency	0,31	0,83	0,17	Standardization	0,27	0,89	0,11
Data security, availability	0,32	0,75	0,25	Communication	0,24	0,87	0,13	Costs	0,20	0,25	0,75
Data completeness	0,14	0,80	0,20	Documentation & Service	0,17	0,17	0,83	Resource efficiency	0,20	0,89	0,11
User friendliness	0,11	0,25	0,75	Risk management	0,12	0,75	0,25	Customer orientation	0,12	0,75	0,25
Simplicity	0,08	0,11	0,89	Training	0,08	0,17	0,83	Competitive advantage	0,11	0,87	0,13
Fault tolerance	0,06	0,75	0,25	Customizability	0,05	0,80	0,20	Strategic fit	0,06	0,83	0,17
Latency	0,04	0,25	0,75	Environment & People	0,03	0,25	0,75	Knowledge gain	0,04	0,89	0,11
Scalability, compatibility	0,03	0,17	0,83								

Fig. 4. AHP for the blockchain application and the data warehouse solution

environment. This approach was also used to design the blockchain solution to store operation data in this study.

V. CONCLUSION

Blockchain technology provides great potential for the manufacturing industry and, as indicated in this contribution, especially the semiconductor industry. Blockchain enables a guaranteed level of security, transparency and immutability that no centralized data storage technology can provide at this time. For the criteria examined, blockchain outperforms traditional, centralized solutions and delivers promising results, especially in terms of organizational and economic criteria. With the acquired knowledge about blockchain in the industry, several more complex use cases can be approached. This may include employing pay-per-use functionalities when certain autonomous parts of the manufacturing process are outsourced to semiconductor foundries to simplify financial controlling. A further outlook for our concept is the integration of more production facilities and business partners into the network, as blockchain is particularly useful when data is exchanged between multiple different parties.

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