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Evaluation of (De-)Centralized IT technologies in the fields of Cyber-Physical Production Systems

Nick Große[1], David Leisen[2], Tan Gürpinar[1], Robert Schulze Forsthövel[2] , Michael Henke[1], Michael ten Hompel[2]
[1]Chair of Enterprise Logistics, Dortmund, Germany
[2]Chair of Materials Handling and Warehousing, Dortmund, Germany

Abstract

In the course of the digital transformation, organizations are not only facing increasing volatility of the markets, but also increasing customer requirements and thus an increasing complexity in production and logistics systems. Therefore, production plants need to become more flexible by transforming conventional production systems to Cyber-physical Production Systems (CPPS). CPPS allow organizations to dynamically react to fluctuations in demand and markets and to introduce new product lines quickly and effectively.

The challenge in implementing CPPS is to handle and store relevant data streams between Cyber-physical objects in a secure but transparent way. As CPPS involve a high level of decentralization, the data storage can either be combined with centralized IT-solutions like a Cloud or utilize decentralized IT-technologies like Edge Computing or Distributed Ledger Technologies (DLT) like Blockchains.

The paper addresses the suitability of centralized and decentralized technologies in terms of dealing with data streams in the fields of CPPS. For this purpose, based on a paper exploration, appropriate evaluation criteria are derived, followed by a comparison of exemplary centralized and decentralized technologies. The outcome is a qualitative evaluation of the supplement of each technology regarding its suitability of dealing with data streams.

Keywords

Cyber-physical Production System; Blockchain; Cloud Computing; Edge Computing; IT Infrastructure

1. Introduction

Cyber-physical Production Systems (CPPS) are envisioned as production system components with information processing and communication capabilities able to execute physical processes within a production system in cooperation with other entities [1]. The expectations towards CPPS are enormous. They are considered as a central factor in the future development of manufacturing [2] or even as the key pillars of the 4th Industrial Revolution [3]. In the field of CPPS, the capture of all data is necessary to monitor the communication between different Cyber-physical Systems (CPS) and for detecting failure potentials [4]. However, the design of CPPS poses a challenge in terms of integration, especially regarding the appropriate IT infrastructure [5]. Various technological approaches are conceivable to create the IT infrastructure. These vary in the degree of decentralisation.

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The present paper examines three different possible approaches of an IT infrastructure for a CPPS, each of which represents an extension of the previous:

1. Cloud Computing as a strictly central approach [6]
2. A Cloud extended by the decentral approach of Edge Computing [7]
3. The combination of Cloud and Edge Computing extended by Blockchain (distributed approach) [8]

The three approaches are evaluated in terms of their suitability for a CPPS. The aim of this paper can be subsumed to the following research questions:

RQ 1: Which requirements are determined on an IT infrastructure through the properties of a CPPS?

RQ 2: To what extent do the IT infrastructures fulfill those criteria?

RQ 3: To what extent is the Blockchain suitable in the handling of various data streams in CPPS?

Section 2 deals with the connection of the three mentioned technologies (Cloud Computing, Edge Computing and Blockchain). Section 3 identifies relevant evaluation criteria for IT infrastructures of CPPS. Section 4 consists of an evaluation of the previously mentioned approaches with regard to the identified comparison criteria, which most important insights are gathered in a consolidation table. Section 5 draws a conclusion of the results followed by an outlook for further research.

2. Background

In this paper Cloud Computing is utilized as an example for a central IT infrastructure, while Edge and Fog Computing will be analysed as a decentral-, and Blockchain as a distributed technology. For a better and common understanding, the fundamentals of each technology are explained in more detail below. In order to address the highlighted challenges in CPPS, data streams have to be handled effectively and efficiently. The degree of complexity increases with the number of CPS in terms of material, information and financial flows [9]. With regard to these streams, IT infrastructures have to offer the appropriate level of decentralization. In this paper, central, decentral and distributed technologies are compared in their interaction to realize the managing of localization data of products or machinery, measure certain characteristics, or enable machine-to-machine communication and payments (see Figure 1).

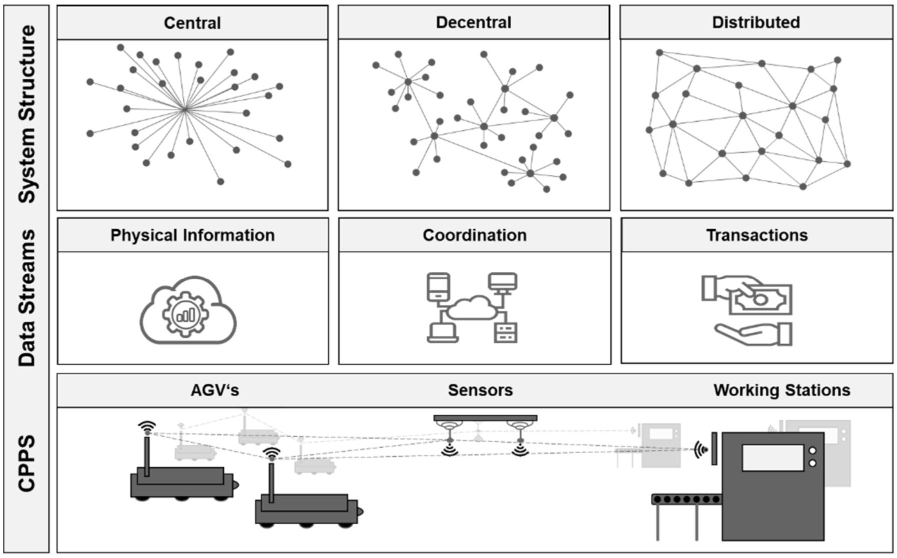

Figure 1: Categories of System Structures and Data Streams relevant for CPPS

According to [7], Edge Computing can enhance the functionalities of Cloud Computing. Combining those two technologies enables a flexible, scalable and reliable production configuration as well as distributed data analytics [10].

3. Review Setting and identified criteria

The central contribution of this paper is the evaluation of the IT infrastructures regarding their suitability for dealing with data streams in CPPS. For this purpose, suitable criteria have to be identified in a first instance, which is done by analysing scientific papers that explicitly deal with IT infrastructures in terms of handling data streams in the topic of CPPS.

The search is composed of scientific papers found by queries done in reputable academic search platforms such as Scopus. Suitable topic-relevant keywords such as ‘Blockchain’ or ‘Edge Computing’ or ‘Cloud Computing’ were chosen and combined with terms referring to the fields of interest such as ‘CPPS’ or ‘CPS’, respectively their full forms. Exclusions are made based on the fact whether the content was referred to CPPS or not. Highlighted terms, which deal with the requirements of data streams referring to CPPS have been chosen as appropriate criteria in this paper. The exploration reveals that, in this context, ‘Scalability’, ‘Latency’, ‘Security’, ‘Processing’ and ‘Flexibility’ were often emphasized requirements and therefore imply a correspondent relevance regarding the problem addressed in this paper [4,11,12]. Further use-case-specific criteria regarding a CPPS are conceivable. However, in addition to their relevance, the criteria already mentioned are primarily influenced by the technologies under consideration, as described in section 4. A more detailed description of each criterion is explained below.

3.2 Scalability

Scalability in this context means the ability of the IT infrastructure to adjust to handle the required data streams of a CPPS, especially concerning the number of connected devices in the network. It is one of the challenges to overcome in manufacturing regarding Industry 4.0 in general [13]. Appropriate structures and methods are necessary to reach a robust CPPS in a changing, uncertain environments [2]. To meet these requirements, the system must be sufficiently scalable. This is also one of the foremost issues in the design of wireless sensor networks [14], which are often part of a CPPS.

3.3 Latency

The implementation of applications in the context of Industry 4.0 in general demands real-time response and reduced latency of the IT infrastructure [15]. It poses a great challenge for industrial data networks to deliver the data to the consumer nodes within the required timeframes [16]. A CPPS, as a distributed embedded system, has additional communication latency in comparison to traditional embedded control systems [17]. However, fulfilling the time constraints is essential for many applications of a CPPS. The operation can become incorrect when exceeding them in a single instance [17] (e.g. an Autonomous Guided Vehicle gets the order to break after a crash). Therefore, the appropriate handling of time in operation systems and computer networks is a main research and development challenge regarding CPPS [2].

3.4 Security

Cyberattacks on CPPS are considered inevitable, which is why Cybersecurity penetration within the manufacturing domain is a need that goes uncontested [18]. The issue of Cybersecurity represents one of the major hurdles in implementing Cyber manufacturing [19] and therefore, is a central issue for future developments regarding CPPS [2]. With an increasing number of CPS with different weak spots and their interconnections, the vulnerability of the whole system also increases [11]. To avoid unintentional disposals or even loss of data, suitable security mechanisms have to be made available [11].

3.5 Flexibility

A certain degree of flexibility of the IT infrastructure is required in a CPPS because of its highly dynamic nature regarding the Computing resources and the physical processes [12]. For instance, the availability of participating devices can change dramatically during deployment [20]. Furthermore, challenges for CPPS regarding the flexibility result from the size of data generated by the devices in modern manufacturing, which can range from terabyte to petabyte for a single data set [21] and the required structures which have to be robust in changing, uncertain environments [2].

3.6 Processing

To capture, manage, and store the extensive data amounts generated in Industry 4.0 applications represents challenges for the industry [16]. To integrate CPS in manufacturing, the systems must be able to analyze big data-information. The generated data sizes for single industrial deployments can reach petabytes for single industrial deployments [13]. Due to the requirement of processing big data in real-time, the use of multimodal interfaces is beneficial [12].

4. Evaluation

4.1 Cloud Computing

Cloud Computing is defined as *'a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable Computing [...] that can be rapidly provisioned and released with minimal management effort or service provider interaction. [...]'*[22]. Cloud Computing comes along with the application of the Internet of Things such as IoT-Clouds and fulfills the requirements of flexibility, uptime, cost and redundancy [23]. One of the biggest advantages of Cloud Computing is the ability to handle different scales of data volume [4,24]. IoT applications like Cloud-based solutions may benefit from a strong ***scalability*** [25]. Nevertheless, Cloud-based solutions are exposed to plenty challenges. Especially, Cloud-solutions are prone to third party cyberattacks [26]. As well as the integrity, the accuracy of the injected data is a vulnerable aspect regarding the validity of the content inside the Cloud [25]. Moreover, it is difficult to track third party attacks [27]. Therefore, ***security*** is a deficit and thus one important challenge of Cloud Computing.

Despite its potential of a high scalability, the quality of Cloud Computing infrastructure is affected or rather restricted by its ***latency*** [29,28]. Thus, with regard to Cloud Computing, latency indicates the throughput speed and thus it represents a so-called bottleneck [30]. For use-cases that require low latency, the single use of Cloud Computing alone is not recommended [31]. The disadvantageous latency properties leads to a loss of data processing [25]. Nevertheless, in combination with machine learning methods, Cloud Computing gains the necessary strength to compete with large data-sizes and facilitates the handling of such volumes through suitable separation and allocation of data sets or rather workflows to external units such as dedicated servers [25,32]. Furthermore, in combination with Big Data, Cloud Computing enables a mighty support system for companies to achieve their ideal production scenario [4]. Despite of its big lack regarding security and latency it possesses a high flexibility due to the possibility of target-oriented allocation of data resourced [33]. Besides the scalability, the resource ***flexibility*** represents one mighty advantage in the use of Cloud Computing for CPS [24].

4.2 Edge and Cloud Computing

Since the Edge Computing principle aligns with the concept of Fog Computing and the two technologies are often referred to interchangeably, we will only use the term 'Edge Computing" in the following [29]. Edge Computing brings a distribution of Cloud Computing capabilities to the Edge of the network, which enables the execution of delay-sensitive and context-aware applications close to the field. The technology also alleviates backhaul utilization and computation at the core of the network [34]. Edge Computing infrastructures move some parts of the system's Computing power from the Cloud to its Edge nodes, which improves latency and mobility of the overall system and reduces the system load of the Cloud. [29]

Edge Computing improves the ***scalability*** through the decentralization of the storage and processing [29]. Due to the improved scalability, Edge Computing facilitates large-scale distributed applications involving multiple plants or factories, which handle data streams from a large number of CPS [29]. When Edge Computing is combined with Cloud Computing, tasks can be delegated depending on their scale. Tasks with a large-scale can be delegated to the Cloud while delegating tasks with a small-scale to Edge-Computing nodes [21]. Besides the possibility of providing low-latency, there is a lack in the ***security***, which leads to a special need in trustworthiness. Due to the mutual change of information between Cloud, Fog and end-user, the whole infrastructure has plenty sources of data retrievals. To maintain the sovereignty of data in the system, corresponding control instances are required. [35] However, Edge Computing devices can be used as a first control instance for encryption and verification [36].

Edge Computing infrastructures move some parts of the system's Computing power from the Cloud to its Edge nodes, which improves ***latency*** and mobility of the overall system and reduces the system load of the Cloud. Furthermore, Edge Computing allows near-real-time applications for analyzing process data at shopfloor level or controlling CPS like machines or industrial robots. It provides low-latency in a distributed network [35]. The wide spread geographical nature of the edge computing technology allows proximity processing close to the shopfloor and consequently a lower latency than in purely Cloud-centric IT infrastructures [29]. The bottleneck problem regarding the data transmission and storage already mentioned in the single Cloud Computing can be bypassed by the principle of Edge Computing [35]. It also supports the ***processing*** of tasks immediately or rather in real-time [7]. Edge Computing provides limited processing power [37], whereas the Cloud takes over large or powerful processing tasks [31]. In terms of ***flexibility***, Edge Computing solutions offers the ability to flexibly (re)configure real-time automation flows [29,37].

4.3 Edge-Cloud-Computing with Blockchain-Technology

The third stage observed is an IT infrastructure supplemented by the use of private Blockchain solutions. A Blockchain is a DLT that stores data in time stamped blocks. The blocks are irreversibly chained to their respective predecessors by hash functions [38]. In contrast to public Blockchains, private solutions offer a permissioned access and adjustable level of transparency. In the scenario of handling data streams, the distributed nodes of a private Blockchain can be used as a general purpose database. All data stored, therefore benefits from Blockchain advantages, such as timestamps, immutability and possible verifiability. Especially in an environment with numerous CPS interacting with each other, these characteristics can be of use to store evidence about interrelated communications and payments. [39] The infrastructure of the Blockchain provides the involved parties with an insight into all transactions made, as they are stored in the distributed system in a traceable manner [8]. Furthermore, it is possible to have Smart Contracts run on a Blockchain, which are thus able to trigger and run contract arrangements automatically or in future autonomously and thus opens up an enormous potential for the automation and autonomy of business processes [40].

Blockchain technology has the potential to truly decentralize the way data is stored and managed without the need of a middlemen or third-party involvement. Due to the distribution of data across the network nodes, data is inherently ***secured*** by not having a single point of failure. [41] In the case of CPPS, Blockchain-based systems could empower organizational units to act decentralized and autonomously on the basis of shared Smart Contracts [40]. Apart from the system itself, that benefits in terms of security through distributed nodes, there also is the data storage technique itself as a unique feature of Blockchain technology. Already by its nature, entries to the Blockchain are stored in blocks and protected against manipulation by cryptography and hashing. In case of an interruption of the hash sequence, this would be immediately identified as a manipulation, visible throughout the whole Blockchain. [40]

The supplementary use of Blockchain solutions can enhance ***flexibility***, as involved network partners have a more transparent information situation. Especially when it comes to cross supply chain problems, partners benefit from the data accessibility of a shared ledger and the use of Smart Contracts. Apart from only ***processing*** data, they can be directly linked to the exchange of any sort of asset. In this context the potential of the Blockchain goes even further, since financial transactions can be managed additionally to data that is related to the flow of materials or information [40]. Based on these advantages, the use of enterprise Blockchain frameworks can lead to more efficient business processes as well as increased transparency and flexibility [42]. On the other hand, even though Blockchains build system bridges between their network partners, they still have to become interoperable among each other. Today, there are many initiatives working on solutions [42,43], but in fact current Blockchain pilot projects still have lack standards when it comes to consensus and hashing algorithms [44]. Hence, most solutions as of now are designed as standalone systems and interoperability between different frameworks still needs to be established. [45].

Another challenge for Blockchain solutions definitely lies within its ***scalability*** and ***latency*** [46,47]. In particular, the number of possible transactions within a fixed timeframe, the block size and number of involved network nodes constitute determining factors for these categories. As the factors differ between different frameworks, but are delimiting most of the current private Blockchain solutions, scalability and latency can be seen as main factors for the slow pace of industry adoption. Furthermore, they constitute a reason why most of the current Blockchain projects still remain in proof-of-concept stage. [48,49]

4.4 Summary

Based on an exploration of scientific paper dealing with data streams in CPPS, suitable criteria for the evaluation of the selected IT infrastructures were identified. The findings of the evaluation were subsumed in a table, which contains the suitability of the IT infrastructure for CPPS in one column and an explanation in a second column, which underpins the respective assignment (see Table 1).

Table 1: Overview of different supplements on IT infrastructures and its affections referring to the identified criteria

Criterion\IT infrastructure	Cloud Computing		Supplemented by Edge Computing		Supplemented by Blockchain Technology	
Rating (R) \ Characteristics	R	Characteristics	R	Characteristics	R	Characteristics
Scalability	◑	- able to handle different sizes of data volume	●	- load-specifc distribution -delegation of data processing tasks	○	-differing transactions per second and number of network nodes -determined storage capacity
Security	○	- prone to cyberattacks - tracking of third parties very difficult - lack of security	◑	- more sources of third-party attacks - Edge devices can perform as a control instances	●	-security of the system through redundant data storage -temper-proof data through time-stamped and hashed blocks
Latency	○	- prone to performance loss through ‘bottleneck” processes	●	- lower latency than purely Cloud-centric IT infrastructures	◑	- limited transactions per second due to the limited time for the creation of new blocks
Processing	●	- able to process large data-sizes - strong in combination with machine learning	●	- allows proximity processing close to the shopfloor	●	- Blockchain has no aim to process large data-sizes -able to process Smart Contracts within a network and involve financial transactions
Flexibility	◑	- resource flexibility - allocation of data streams	◑	- offers the ability to flexibly (re)configure real-time automation flows	◑	- Blockchain frameworks still have to become interoperable - flexibility enhancement due to transparent information status
Legend	●	extensive supplement	◑	partial/conditional supplement	○	no significant supplement

5. Conclusion

The study of scientific work reveals that the requirements for handling data streams in CPPS can be subsumed to the five major criteria ‘Scalability’, ‘Latency’, ‘Security’, ‘Processing’ and ‘Flexibility’. It can be stated, that there are high potentials in the combination of different IT infrastructures, which overwhelms the single use of one technology. The expansion of Cloud Computing through Edge Computing offers advantages, especially in terms of scalability and latency. The adaption of the Blockchain provides potentials in terms of the security. Referring of the scalability, the processing of a high number of transactions, e.g. in a multi-company application, presents a challenge and leads to an interest for further research. Therefore, the supplementary use of Blockchain technology for a CPPS is useful if it requires external entities and a secure and traceable way of data handling. Additionally, the Blockchain-based use of Smart Contracts offers new ways and possibilities to automatize processes, incl. payments, between different CPS.

The criteria were derived from a more technological point view. Thus, financial aspects are not considered in this scope. Furthermore, the evaluation was done qualitatively. Additionally, no differentiation of specific forms of CPPS was done. Apart from Blockchain technology, there is a variety of other DLT such as directed acyclic graphs (DAG) [50], that did not get to reach that much attention in literature yet and aren´t covered in this paper. In order to address our scalability concerns, the handling of CPPS related data streams with different DLT such as DAG should be analysed in future research. Moreover, future research should be performed by testing concrete Blockchain solutions along with Cloud and Edge Computing concerning our derived criteria as well as adding an economic evaluation. As most of the current enterprise projects still remain in proof-of-concept stage, it is necessary to develop more mature pilots for adequate testing.

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Biography

M.Sc. Nick Große (*1992) has been research assistant of the Chair of Enterprise Logistics (LFO) at the University Dortmund since 2019 under the leadership of Prof. Dr. Michael Henke. He is a member of the research training group 'Adaption Intelligence of Factories in a Dynamic and Complex Environment'(GRK 2193).

M.Sc. David Leisen (*1993) had been research assistant of the Chair of Material Handling and Warehousing (FLW) at the University Dortmund since 2019 under the leadership of Prof. Dr. Michael ten Hompel till September 2019. He is working at 'Deutsche Telekom"-company in Bonn since October 2019.

M.Sc. Tan Gürpinar (*1991**)** has been research assistant of the Chair of Enterprise Logistics (LFO) at the University Dortmund since 2018 under the leadership of Prof. Dr. Michael Henke. His research focuses on blockchain technology in the field of supply chain management.

M.Sc. Robert Schulze Forsthövel (*1992) has been research assistant of the Chair of Material Handling and Warehousing (FLW) at the University Dortmund since 2018 under the leadership of Prof. Dr. Michael ten Hompel. He is also member of the research training group GRK 2193.

Prof. Dr. Michael Henke (*1971) has been the chairholder of the Chair of Enterprise Logistics (LFO) at the University Dortmund and director of the Fraunhofer Institute of Material Flow and Logistics (IML) since 2013. He is also an adjunct Professor for Supply Chain Management at the School of Business and Management at the Lappeenranta University of Technology in Finland since 2015.

Prof. Dr. Dr. hc. Michael ten Hompel (*1958) has been the chairholder of the Chair of Materials Handling and Warehousing (FLW) at the University Dortmund since 2000 and managing director of the Fraunhofer Institute of Material Flow and Logistics (IML) since 2004.