A Multichain Architecture for Distributed Supply Chain Design in Industry 4.0

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Abstract. The Fourth Industrial Revolution is centered around a self-organized production. Cyber-physical systems can be used to collect and share data for tracking, automation and control as well as evaluation and documentation. This has a wide-reaching impact on business models. Instead of a linear approach, concentrating on a single company, the focus needs to be on the complete production ecosystem represented by a dynamic and self-organized network, including the supply chain. The interconnectedness of the cyber-physical systems in these networks is rooted in the Internet of Things, but also shared business processes. Performance, stability, security as well as data integrity and access control hereby represent a major contributing factor, calling for a new concept of information processing systems.

The blockchain is a distributed ledger combining cryptographic and game-theoretic concepts, which enable immutable transactions and automatic consensus of the parties involved about its state. Blockchains have evolved as a fast-developing technology, promising increased efficiency and security in many scenarios, especially use cases that primarily rely on all kinds of transactions.

The paper follows a design science approach, examining the implications of blockchain and the industrial Internet of Things in Industry 4.0 (I40) on supply chain management. I40's implications on supply chains are discussed and connected with favorable characteristics of blockchain technology. Based on this analysis, requirements for a decentralized enterprise information processing system are derived, resulting in a reference model for distributed supply chains of I40.

Keywords: Blockchain · Supply chain · Industry 4.0 · Distributed supply chain · Multichain

1 Introduction

I40 represents a paradigm shift in traditional manufacturing and production techniques towards a self-organized production, meaning that products can control their own manufacturing process, which has the potential to transform the complete value chain [1, 10, 12]. "In the world of Industrie 4.0, people, machines, equipment, logistics systems and products communicate and cooperate with each other directly. Production

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and logistics processes are integrated intelligently across company boundaries to make manufacturing more efficient and flexible. This facilitates smart value-creation chains which include all of the lifecycle phases of the product" [11]. The inclusion of all lifecycles in the planning and engineering process is called a through-engineering across the entire value chain [13]. The evolution of I40 emanates from a technology push caused by the second machine age [2, 10]. At the same time, an application-pull enforces the systematic implementation of the above technologies. This application-pull is triggered by sustainability requirements, shorter development periods whilst the demand for flexibility has increased, emanating from a shift from a seller's to a buyer's market and resulting in 'batch size one'. Furthermore, the aforementioned conditions call for faster decision-making processes that will require a higher degree of decentralization [10]. Current business processes as well as management and organizational structures are seen as the potentially biggest hurdle to access the potential advantages of I40 [9].

The paper at hand motivates the innovation of existing information processing systems in the context of I40 and examines possibilities to meet the specific requirements in this context through the application of blockchain technology.

Other than taking a technical perspective on blockchain implementation in I40, a multichain-architecture involving various technologies under development is proposed that facilitates distributed supply chains in future industry ecosystems and lays a foundation for future development towards fully automated multi-stakeholder I40 applications. The research methodology is based on a literature research, a technology monitoring and design science approach, based on the information systems research framework of Hevner et al. [8] as a problem-solving paradigm has been used for the elaboration of the multichain architecture. More specifically, this paper utilizes the three-cycle view of design science research [7]. The initiation of the relevance cycle was achieved by a technology monitoring that has been conducted to identify the current status quo of blockchain application in supply chains. A technology monitoring is part of a set of methodologies for technology forecasts [4].

2 Implications of Industry 4.0 on Supply Chains, Company Structure and Information Processing Systems

Schrauf, Berttram [14] see the digital supply chain at the center of the digital enterprise. When projecting the self-organization approach of I40 onto supply chains, the IoT most certainly provides the most valuable technology for the supply chain, providing optimal visibility of and information on materials and products that are the basis for automation processes. In a supply chain, equipment and upstream products can be equipped with IoT devices so that the materials or upstream products become objects in the IoT. This can be utilized to achieve a decentralized and self-coordinated material flow [1].

Additionally, the mass production of individual products affects supply chain strategy and design, since individualized products are necessarily demand-driven. This resembles a traditional make-to-order process, in respect of the individuality of products and should result in an agile strategy. I40, however, allows for new concepts for the management of global production and supply systems. With its self-organization approach and real-time communication, I40 promotes efficiency in supply chains, which, as a result, can still be pull-based because they do not need to rely on stock in later production stages. Distributed sub-systems can become interconnected and communicate directly and in real-time. Demand-forecasting causing the bullwhip effect can be substantially reduced thanks to real-time information, also enabling the automatic redirection of material flows to another production site in case of an outage [1]. Thus, supply chains will become hyper-reactive in a way that is almost proactive. Machines equipped with sensors, actuators and visual systems can fulfill orders they have received from other machines, which these in return have commissioned based on e.g. sensor input from the physical environment.

Industry 4.0 requires information processing systems to promote integrability and interoperability that enable versatile and flexible production processes. “The most successful companies will use better communications to integrate suppliers and customers’ needs into all value-creation activities” [13]. This will have implications on overall supply chain design, implying a paradigm shift from a linear supply chain design to a network-centric one. “The vertical networking of Industry 4.0 requires new IT solutions. In many cases, existing IT infrastructures are very fragmented and result in poor networking” [13].

The through-engineering over all lifecycle phases means that data must be securely available across the entire value chain. The demand to share data in many interrelated networks requires information access to be restrictable with an efficient users’ rights management and to protect all data against cybersecurity risks. The vision of ‘Ubiquitous Computing’ that connects devices and opens up information processing and management information systems to other systems calls for a new holistic security concept. “With the increased connectivity and use of standard communications protocols that come with Industry 4.0, the need to protect critical industrial systems and manufacturing lines from cybersecurity threats increases dramatically” [12]. Connected machinery and asset information in the cloud pose a possible threat, since they will arouse the interest of hackers. “The extensive networking (…) and the high levels of data sharing involved in I40 will greatly increase the demands made on data security” [13].

Security concerns can represent a bottleneck in I40, which can be addressed by blockchain technology. Blockchain technology represents a tamper-proof way to record transactions in a distributed digital ledger and is supposed to have a great impact on the design and the implementation of digital business processes, bringing along the potential to streamline and accelerate them [15]. It promises to enable an infinitely scalable ledger that can be shared between all participants in a supply chain and that can be utilized to securely store all asset tracking data in real-time. While some solutions for blockchain-enhanced, distributed supply chains are already under development, the technology monitoring has shown that no market player has pulled clear with a mature and broadly applicable product that supports open standards. In general, standardization in the blockchain space seems a long way off.

3 Blockchain Technology

Blockchain technology embeds trust in a network through immutable data records and distributed network consensus, exchanging the need for intermediaries with cryptographic trust, thereby accelerating processes [15]. Similar to the provisioning models of cloud computing blockchains can be permissioned networks or unpermissioned networks depending on their purpose of application. Public blockchains provide better censorship resistance and, through their openness, can be used by many entities, nurturing network effects [3]. Certain aspects of private or consortium blockchains can be valuable for enterprise applications. In private chains or consortium chains, functionalities such as improved data privacy, configuring blockchain rules, reverting and modifying transactions can be of advantage. The implementation of consensus mechanisms such as PoA provides much faster transaction finality and leads to increased transaction speed and decreased transaction cost, promoting scalability. Even if the decentralization aspect is diluted, private blockchains still provide cryptographic authentication, audibility and features such as zero-knowledge proofs. Smart Contracts extend the capabilities of the blockchain as a secure distributed ledger to also enable automated and secure modifications of information on the blockchain [15]. They can be used to create arbitrary rules on a blockchain and can encapsulate complicated business logic that automates transactions based on supply chain events.

Utilizing smart contracts, tamper-proof tracking and trustless transactions, the blockchain in connection with the IoT enables automated operations within an SCM system [15]. Regarding IT security, blockchain technology offers the appropriate measures through public key cryptography and cryptographic hash functions. Security is furthermore embedded by a decentralized network consensus amongst several parties with disparate interests. This is especially useful, when parties don't want to exchange information directly, but need to verify the integrity of this information. Because every participant in the blockchain network has a copy of the ledger and the blocks form a chronological sequence of records, data manipulations are transparent and easy to reconstruct.

Furthermore, supply chains can become more trustable through the irreversibility of transactions. The embedded trust of the blockchain requires less clearances and reviews and can give unique identities to machines in the IoT so that machines can autonomously decide, which machine to trust and which services to offer to which machine. This automation potential is especially important for the reactiveness and agility of I40 supply chains; e.g. in case of a blocked transport route in an adaptive multimodal transport chain, goods can be automatically redirected, utilizing IoT information. Thanks to blockchains, the rapid change of plan is accountably trackable and payment streams regarding compensation for transport can be redirected in a trusted manner. In both cases, a blockchain is a suitable infrastructure. In all cases, an SCM tracks and monitors relevant production and product information. This information can refer to the parties involved in a certain transaction, the state of a product, e.g. its price or quality, a transaction or manufacturing date and location. The concatenation of blocks in the blockchain ensures that all data can be traced back to its very origin, which would be the raw materials in most cases. This can have a great impact an ecological responsibility of manufacturing and can be utilized to satisfy environmentally and socially conscious customers, since they can be confident in the data's integrity.

Taken together, the blockchain could improve efficiency and transparency in supply chain, but also increase the visibility of goods within them. Building confidence in supply chain networks has, until now, been costly because it is effortful and exhaustive, requiring a lot of intermediaries or trusted relationships between company employees [5].

4 Integrating Blockchains into Supply Chain Management Systems

Future enterprise information processing systems will be built on a network-centric design and support decentralized decision making. Ecosystems thrive on compatibility and openness for innovations. Enterprise application of blockchains is inherently more valuable when it incorporates an interoperable, versatile concept instead of only focusing on an isolated use case. This way, a complete ecosystem of intertwining systems can be created. In [5, 21–25] blockchain is presented as a freight logistics solution, a solution for improved pharmaceutical security, an integrated food supply chain and real-time logistics respectively. Also, blockchains is presented as a way to reduce fraud, increase supply chain visibility and to provide better means for supply chain optimization as well as demand forecasting.

Ideally, an ecosystem of autonomously communicating applications is able to provide sufficient automation capabilities for I40. Systems big enough to cope with a large amount of data, fast enough to cope with a high frequency of transactions, specialized to be extremely secure for certain purposes or to be easily accessible for customers have to be split up in subsystems that need one hub, bringing them all together. A beneficial ecosystem would be able to incorporate more specialized solutions for certain business cases, solutions specialized on IoT communication and enterprise systems focused on e.g. security and auditability. To guarantee future-proofness through openness and versatility, the bedrock of this ecosystem is therefore a hub that is optimally not provided by a proprietary solution and sufficiently decentralized. To construct such a system, three essential pillars are identified.

4.1 Core Functionality

Given the scenario of a consortium of supply chain network, participants that do not necessarily trust each other but mutually benefit from cooperation, a blockchain can provide trusted interactions without a central authority or intermediaries.

The toolkit for such a blockchain can be the Parity Ethereum Client. Each Parity Ethereum Client runs a full or light node in the P2P network and can be paired with a user interface, which can be customized to support file management, business processes, smart contracts configuration as well as account and rights management. On top, the client features permissions. Permissions span the configuration of an individual node's role as well as the definition of which nodes can connect to the network and connect to each other. On an account level, the type of transactions individual nodes can perform can be constricted. Furthermore, it is possible to regulate gas price within the blockchain and to introduce new validators to the blockchain in a distributed manner through any arbitrary rule, that can be implemented in a smart contract, e.g. a majority vote.

This offers a possibility to set up a configurable Ethereum-based blockchain for the decentralized and tamperproof exchange of supply chain and other relevant documents, whilst maintaining enough flexibility to implement the design requirements of an individual consortium network. Through a ‘pluggable consensus’, namely the possibility to choose a consensus algorithm – PoW (Ethash), PoA (Aura, Tendermint) and potentially PoS (Aura, Tendermint), but theoretically any functioning implementation of Byzantine Fault Tolerance.

4.2 File Storage

In the attempt to offer a distributed storage capability that is consistent with the decentralization paradigm, certain aspects of the traditional blockchain concept aren’t useful for data storing purposes. Confirmation time of blocks is not acceptable for common data queries and not all data needs to be stored forever and immutable, either because it is to be actually replaced, has expired, or for simple reasons of costs for capacity. However, this only holds true if data is stored on the blockchain itself. P2P file systems such as IPFS (ipfs.io), decentralized cloud file storages such as Storj (storj.io) or Ethereum Swarm (github.com/ethersphere/swarm), but also decentralized database systems such as OrbitDB (https://github.com/orbitdb) or Bluzelle (bluzelle.com) can provide a far higher performance and provide means to be in consistence with the overall decentralization concept of a distributed supply chain.

IPFS is already integrated into the Parity technology stack. Built on a set of proven core technologies with the vision of a permanent World Wide Web, one of IPFS’s purposes is that of an encrypted file or data sharing system. The link to (a large) amount of data can be stored in an IPFS link that is included in a blockchain transaction. This way the data becomes timestamped and is secured on the blockchain. At the same time, this provides a way to make the content addressable. The hyperlinks stored in the blocks form a Merkle directed acyclic graph (DAG) that supports the building of a versioned distributed file system. The implemented BitSwap protocol for block exchange ensures that also rare files are sufficiently distributed in the system.

The functionalities descried as hitherto have already been bundled by Parity Technologies in a product called SEDACS [19], which is licensed under a commercial license, but since most of its components are open sourced, it can be recreated with reasonable effort. When building on top of Parity Ethereum, Secret Store or other open source technologies of Parity Technologies and IPFS, customers can choose to connect these parts on their own or to resort to SEDACS. All technologies except SEDACS are licensed under a GNU GPLv3 free copyleft license, meaning that these technologies can be implemented for commercial use, unless they are redistributed within a commercially licensed software package. In comparison to e.g. Chronicled’s offering SEDACS does not rely on central vendor servers or similar centralized services, but instead is based on federated servers, owned by each participant in the supply chain consortium or potentially by certain third parties that do not trust the consortium with verifying the data.

4.3 Interoperability

The need for interoperability on a distributed supply chain accrues from individualized product and service development, resulting in connected processes handled by different channels [10]. Because I40 spans the complete product lifecycle, interoperability of IT systems is indispensable. Cyber-physical Systems (CPS) along the value chain have to be interconnected in an overarching network and integrated in a distributed IT infrastructure [6]. Traditionally, interoperability can be achieved in a lot of ways and mainly concerns compatible data formats or APIs. The problem with these is, though, that they are not immutable and can be copied without notice. Blockchains can provide these security, but up to now always a closed system. I40 enterprises will presumably deploy private and consortium chains for their purposes, but the need for flexibility and the integration and cooperation of changing partners in a supply chain network requires these chains to be possibly open to others.

Polkadot is a ‘heterogeneous multi-chain’ concept. “The heterogeneous nature of this architecture enables many highly divergent types of consensus systems interoperating in a trustless, fully decentralised ‘federation’, allowing open and closed networks to have trust-free access to each other” [18]. Among multichain protocols, Polkadot has been identified as most suitable as it allows for the interaction of smart contracts located in disparate blockchains. It aims at providing a central relay chain, which decouples the consensus mechanism from the state-transition mechanism so that blockchains running on different logics can be linked. Another multi-chain approach is Cosmos an “inter-blockchain commu-nication protocol” [20]. The “Cosmos Hub” represents the equivalent of a relay chain, but since Cosmos is focused on the secure interchange of tokens whilst Polkadot focuses on the secure exchange of data in general, the latter has been identified to be more suited for a supply chain network application as it allows for the in-teraction of smart contracts located in disparate blockchains. The relay chain functions as a bedrock for numerous parallel chains, called parachains. Data from parachains is forwarded through the relay chain. This forwarding takes place in a validated parachain block via a Remote Procedure Calls (RPC).

Polkadot is designed for both public and private/consortium chains, opening up the possibility to integrate the two. Polkadot is also expected to be interoperable with the public Ethereum blockchain [18]. This opens up possibilities for the inclusion of data hosted on the public Ethereum chain, which could be an elegant way to integrate customers in an otherwise private/consortium enterprise blockchain setting.

5 Distributed Multichain Supply Chain Design

Based on the previous analysis, we suggest the following architecture for distributed supply chains of I40, in which

- **Parity SEDACS** provides blockchain-federated handling of asset tracking-data and documents, e.g. shipping documents or certificates.
- **Polkadot** is used as a connector from SEDACS to IoT blockchains that are suited to handle the amount of IoT data and provide M2M communication, but also to any

other possible chain such as financial institutions and insurances or the public blockchain network.
- **IoT** blockchains can be individually maintained by network participants and relevant asset-tracking data is forwarded to SEDACS (Fig. 1).

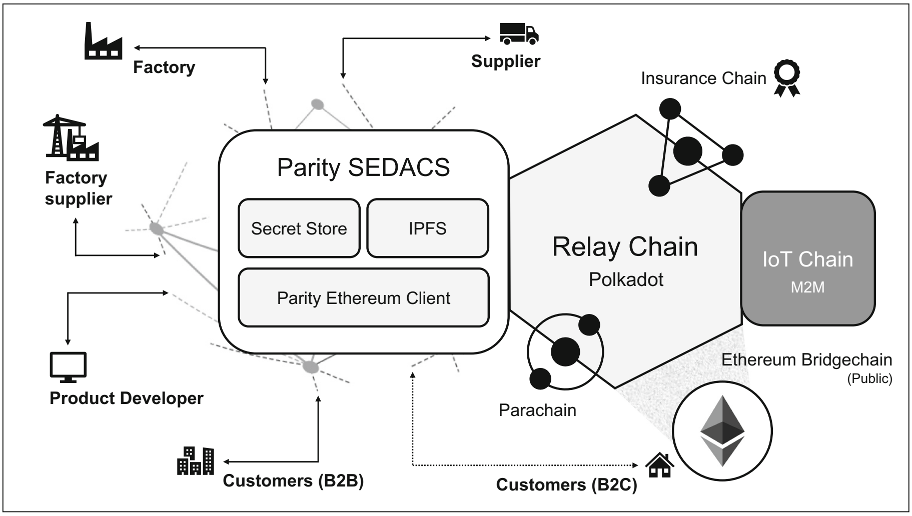

Fig. 1. Distributed supply chain design, partially based on [6, 18].

This answers the need for secure authentication, non-repudiation and integrity of data in a decentralized network and aims at combining several best-of-breed systems. Each of the chains focuses on further attributes – authorization, auditability and governance, availability and scalability – while always serving the purpose of security and are described in further detail in the following subchapters.

5.1 Corporate Network – Authorization, Audibility and Governance

Corporate network participants are directly connected in their own Ethereum-based chain. The overall functionality is based on Parity SEDACS, which bundles several core technologies. SEDACS allows for decentralized exchange of documents and will further promote decentralized decision making, the governance of network features and participants and the management of authorizations. It will as well provide a tamper-proof audit trail for internal and external review for e.g. auditors. PoA offers instant transaction confirmation by the trusted nodes, which implies freely configurable block times suited to individual needs, and high security, since the nodes within the corporate SEDACS network are, in a real-world scenario, more trustable than random nodes in a public network, since their identity is known and at stake. Moreover, malicious actions, e.g. in case a node is taken over, are countered thanks to the decentralization of validation rights.

Thus, a closely knit corporate network can be established, in which new actors can be introduced upon encoded rules. The consortium type of blockchain with PoA supports privacy and security as well as reactivity and configurability, so that individual corporation requirements can be mapped, while still maintaining the major advantages of blockchain technology. The exclusivity of the corporate blockchain enables a close cooperation of companies, but isolates this chain from wider networks, such as a network with customer identities and the IoT. Therefore, Polkadot is used to connect the more exclusive corporate network – offering higher performance and privacy – to the outer world, providing availability for customers. Customers thus are included into certain activities within the corporate network's I40 value chain. Since I40 heavily relies on IoT data, this data is also selectively included from external blockchain sources. Furthermore, Polkadot offers the opportunity to include other corporate networks to connect e.g. financial institutions and insurances that provide services to the corporate network.

5.2 Customer Integration – Availability

Geisberger, Broy [6] foresee the direct integration of customers into a decentral CPS. The relay chain enables a solution, which differentiates between B2B and B2C customers. While B2B customers are highly engaged and have their own security arrangements, B2C customers are naturally less involved in the value chain of a product of their choice. Thus, B2B customers are still directly integrated in the information processing system represented by SEDACS. B2C customers, on the contrary, are not required to have a permanent account for SEDACS that they have to maintain and that open possible security risks. However, customers as private persons will most likely keep their online identify on a secure blockchain solution for Identity Verification (IDV) and Know-Your-Customer (KYC) purposes. Civic (civic.com) and Blockstack (blockstack.org) propose current solution not based on Ethereum, while others such as SelfKey (selfkey.org) plan to provide a KYC solution for Ethereum. Either way, publicly accessible IDV and KYC systems can be integrated via the Ethereum bridgechain or a parachain. If they are Ethereum-based, they can also be built on top of the same Ethereum chain that runs SEDACS.

5.3 IoT Connection – Performance

The amount of data in the IoT requires different blockchain specifications other than needed for document sharing capabilities as in SEDACS. For simple value transfer infrastructures based on Unspent Transaction Outputs (UTXO), a DAG can be deployed as well to make single transactions interdependent [18]. A DAG-based ledger is being developed e.g. by IOTA with Tangle (iota.org). This approach is (at least momentarily) impractical regarding state changes: the ability to communicate a system state is a prerequisite for systems interaction [18]. Other blockchain solutions that could enable M2M communication in the IoT are developed by Filament (filament.com), ubirch (ubirch.de), Engima (enigma.co) and Moeco (moeco.io). Most importantly, IoT blockchain parameters can be aligned to promote transaction throughput, while neglecting transaction ordering.

Even if no prevailing solution can be identified yet, the interoperability approach of Polkadot makes it possible to realize the interconnection of any IoT focused blockchain with a document- and access rights-focused blockchain. With Polkadot, a system providing fast and efficient M2M communication is most favorable blockchain-based for maximum compatibility but could possibly also be DAG-based or simply incorporate IoT data via a blockchain oracle.

In an application scenario, certain IoT tracking data is forwarded to a SEDACS Ethereum-based private chain, where the involved parties manage this data and use it for further processing and administration. Conversely, IoT objects can be required to wait for permissions that are granted in SEDACS and then forwarded to the IoT chain.

6 Conclusion

In a first step, changing demands for information processing system due to the current developments around I40, especially in respect of SCM, have been outlined. The research design was based on the design science approach of Hevner et al. [8], while limiting the scope to the first half of the design cycle. Following, the high-level features of a blockchain were introduced and beneficial factors that can address the needs of I40 SCM systems were touched. Subsequently we proposed a design for distributed I40 supply chains, based on the design science approach.

The outlined design of distributed I40 supply chains incorporates technologies that are as well still under development. Their successful finalization is a prerequisite for the functioning of the solution as presented. Furthermore, the initial solutions will most likely fall short of the centralized systems. Still, the suggested advantages exist on a theoretical level and the utilized decentral systems are under heavy development, fueled by public interest in and experimentation with cryptocurrencies and tokens. The limitations described above can best be characterized by Foster's S-Curve for assessing technological threats, in which the current state of new technology is less capable than existing technology, but the new technology incorporates higher potential.

The paper has cycled through the first of three cycles of the design science approach. Future research should close the first cycle with concrete field tests. The results can then be used to cycle through phases 2 and 3. These would include evaluating the technology design as well as the induction of new theoretical concepts based on the results of the evaluation.

The concepts of blockchains that act as a hub and connector for disparate blockchains inherits a much broader vision and potential than presented in this paper and can have far-reaching consequences in many areas. The more there are application scenarios, the faster and more diligent the development of such technologies will be, facilitating the development of a distributed I40 supply chain design. Furthermore, the design with Polkadot will also enable Ethereum-based chains to interact with other blockchain technologies likely to be used in a corporate context such as Hyperledger Fabric (hyperledger.org/projects/fabric) or Quorum (jpmorgan.com/global/quorum), but also enable customers to pay with a cryptocurrency non-native to the corporate network within the latter.

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