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Blockchain-Based Cloud Manufacturing SCM System for Collaborative Enterprise Manufacturing: A Case Study of Transport Manufacturing

Alice Elizabeth Matenga * and Khumbulani Mpofu

Department of Industrial Engineering, Tshwane University of Technology, Pretoria 0183, South Africa
* Correspondence: matengaae@tut.ac.za

Abstract: Sheet metal part manufacture is a precursor to various upstream assembly processes, including the manufacturing of mechanical and body parts of railcars, automobiles, ships, etc., in the transport manufacturing sector. The (re)manufacturing of railcars comprises a multi-tier manufacturing supply chain, mainly supported by local small and medium enterprises (SMEs), where siloed information leads to information disintegration between supplier and manufacturer. Technology spillovers in information technology (IT) and operational technology (OT) are disrupting traditional supply chains, leading to a sustainable digital economy, driven by new innovations and business models in manufacturing. This paper presents application of industrial DevOps by merging industry 4.0 technologies for collaborative and sustainable supply chains. A blockchain-based information system (IS) and a cloud manufacturing (CM) process system were integrated, for a supply chain management (SCM) system for the railcar manufacturer. A systems thinking methodology was used to identify the multi-hierarchical system, and a domain-driven design approach (DDD) was applied to develop the event-driven microservice architecture (MSA). The result is a blockchain-based cloud manufacturing as a service (BCMaaS) SCM system for outsourcing part production for boxed sheet metal parts. In conclusion, the BCMaaS system performs part provenance, traceability, and analytics in real time for improved quality control, inventory management, and audit reliability.

Keywords: SCM; cloud manufacturing; industry 4.0; event-driven microservices; permissioned blockchain; Kubernetes; stateful

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1. Introduction

Industry 5.0 (i5.0) is a new sustainable value-driven era of hyper-connected systems to solve complex challenges, whereas industry 4.0 (i4.0) is signified by intelligent and connected digitalized machines and systems [1,2]. Cloud-based information management has become fundamental in value creation for successful organization management [3]. Enterprise collaborations in a manufacturing supply chain are set to benefit from the full potential realization of industry 4.0 technologies, incorporating a synthesis of value along the value chain. Supply chains (SCs) are complex inter- and intraorganizational systems which are dependent on up-to-date information flow, to improve system efficiency through information sharing [4]. In the development of smart cities, large moving bodies for transportation become safety-critical cyber-physical systems (CPSs), i.e., automobiles, railcars, airplanes, ships, etc., whose assembly is dependent on complex, distributed, and networked SCs, where the integrity of parts is critical for safety and operational performance [5].

Whereas i4.0 focuses on developing cognitive CPSs, i5.0 integrates metadata and artificial intelligence (AI) to identify sustainable and circular value chains for industrial decision-making [6]. I4.0 adoption in manufacturing enterprises is characterized by merging production to logistics between the physical and virtual worlds [7], enabling vertical and horizontal system integration for synchronized business operations. Computational intelligence and sensing technology have been instrumental in developing networked heterogenous machines, systems, and facilities for autonomous data exchange at high speed, bringing optimized control and management to industrial processes [6,8].

However, in March 2020, 75% of companies globally reported disruptions within their supply chains due to transportation restrictions [9], resulting in the promotion of product localization. The COVID-19 pandemic brought with it multiple unanticipated factors that industries had to grapple with simultaneously, such as deaths of employees, the quarantining of infected employees at different intervals, disruption in travel, and disruption in production lines as suppliers were experiencing the same adverse effects. Post-COVID-19 pandemic, organizations have two options: either adopt industry 4.0 technologies such as CM, industrial internet of things (IIoT), blockchain, etc., in order to mitigate risks associated with the COVID-19 pandemic or maintain their traditional ways of doing business.

Technology has disrupted traditional information systems with new advancements, leading to new value creation and business models. The supply chain is the heart of business, which allows for seamless material and product flow for multiple manufacturing and assembly activities [10]. CM is a new service-oriented business model, which adopts a distributed and intelligent manufacturing network, using cloud resources to offer multiple services [11,12]. CM is a critical element of industry 4.0, which is built on cloud computing (CC), big data, and AI through vertical and horizontal integration and the networking of resources and services [13]. However, i4.0 requires the interconnectedness of machines, production systems, and IT systems, significantly highlighting the importance of software development, which is the main impediment to the adoption of industry 4.0 [14].

Ivanov et al. [15] highlighted that the "cloud supply chain integrates all operational processes (e.g., logistics, warehousing, manufacturing, sales, and returns), all supply chain flows (i.e., material, informational and financial), and all the supply chain actors (i.e., suppliers, manufacturers, distributors, and customers) in a digital ecosystem." However, SCM is a core business operation that is defiantly resisting digital transformation, as is still dependent on spreadsheets, enterprise resource planning (ERP) systems, and manufacturing execution systems (MES), making strides in digital transformations futile [16]. SCs and planning ISs have been supported by ERP and MES software systems, which are built on traditional monolithic architecture and no longer suffice the rapid development and expansion for improving scalability in operations. In addition, in a manufacturing supply chain, BD generated by each organization's information system is fragmented and isolated. As such, companies need to adopt new technologies and business strategies to enable agile and scalable applications [17].

CC infrastructure was previously delineated into three offerings, namely infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS) [18]. Recently, serverless computing has become a prominent and preferred CC style for developers. Serverless computing was first introduced in 2014 by Amazon Web Services and later adopted in 2016 by Google Cloud and Microsoft Azure [19]. Hence, serverless computing is a newly established cloud-native paradigm, which represents an evolution in the cloud application deployment of applications, services, and the development of abstractions, programming models, and platforms [18]. In serverless computing, resources are dynamically provisioned at run-time, along with their configuration and management through event-driven allocation and control [20]. Consequently, this adds an abstraction layer to PaaS, whilst taking away backend server management [19]. Serverless computing allows developers to run event-driven and granular applications without addressing operational logic [21]. As such, SC operations are deployed as microservices, i.e., suites of small functional services which operate autonomously and are favourable to cloud-native applications [22].

Lui et al. [23] highlighted that the relationship between cloud manufacturing and new industry 4.0 technologies is barely discussed, although the integration of these technologies has a bearing on an organization's internal operations and management. SCM systems are proprietary information value chain systems, exposing the IS to cyber risk [24]. Blockchain is a disruptive technology for the 21st century [25], which enhances the flexibility and security of collaboration amongst stakeholders. As a notable priority technology, blockchain is being implemented in every facet of business and it is expected that 10% of the world's GDP shall be stored in a blockchain system by 2027 [26]. Kumar et al. [27] gave an in-depth review of the application and use case of AI and blockchain technologies. Orji and Liu [28] identified that in the field of sustainable studies, the application of system dynamics is relatively new, which justifies the multiple opportunities relative to sustainable supply chain management. Hence, multiple organizations are looking into automating the tracing of their enterprise data using blockchain technologies [29]. Subsequently, by integrating emerging technologies, a blockchain-based cloud manufacturing SCM system was developed for a railcar manufacturing enterprise through the integration of a private blockchain with a cloud manufacturing system for boxed sheet metal parts.

This paper presents a case study on a railcar manufacturing supply chain for production of boxed flat sheet metal parts. A two-tier manufacturing supply chain, i.e., railcar operator-railcar manufacturer and railcar manufacturer–manufacturing supplier, exists within the SC. The railcar manufacturing enterprise both manufactures and outsources parts and components, which are assembled to produce a railcar onsite. As a large original equipment manufacturer, the railcar manufacturer is subject to undergo auditing to ensure that there are no fraudulent activities within their business operations. Therefore, traceability in the SC becomes key to ensuring audit reliability. Provenance is a tracking system of granular activities that enables organizations to orchestrate supply chains for demand–supply management [30]. Since boxed sheet metal parts production is outsourced for assembling the railcar at different lead times, inventory management involves part manufacturing for both new assembly and re-assembly for a railcar. The lead times to assemble boxed sheet parts are affected by material inputs from a supplier, the number of parts, machine availability, the process undertaken, and the process time lag.

Various sheet metal part designs are used for the railcar (re)assembly process, whereby part tracing leads to the generation of BD. ERP is being implemented to produce the railcar, whereby electronic and physical data capture results in BD generation along the assembly line and a paper trail, respectively. Various inaccuracies are encountered whilst conducting work such as volume variability, misappropriation between supplier and order, wrong specifications, etc., whereby the use of different information management systems further espouses these challenges [26]. Gupta et al. [31] proposed a cloud-based ERP to enhance sustainable performance using cloud operations. Vincent et al. [32] built a blockchain on top of an ERP using the database layer, a technique that duplicates data capture. Additionally, these systems focused on iterative designs which are built on monolithic legacy systems.

The COVID-19 pandemic has resulted in a shift in conducting business, whereby most businesses were forced to adapt to the new way of working. Blockchain has been identified by the European Parliament as a key and notable technology for combating COVID-19, as it is instrumental in creating a robust supply chain [33]. As such, cloud manufacturing and blockchain have become crucial technologies in manufacturing enterprises. Section II highlights the concept development for an integrated SCM, section III demonstrates the methodology adapted in developing a blockchain-enabled supply chain, section IV illustrates the design of blockchain and cloud manufacturing to supply chain management in a digital economy, and section IV presents the results. The key limitation of the developed system is that the system's strength in the event of cyberattacks is yet to be explored.

2. Literature Review

Related works in the literature show that strides have been made in merging technologies. Table 1 below shows the work conducted in digitizing various aspects of a manufacturing supply chain.

Table 1. Summary of related work and gaps identified in literature.

Author(s)	Year	Topics	Work Conducted	Gap
Patera et al.	2022	DevOps	Convergence of OT/IT for edge computing.	The system is not built for cloud native applications, as the designed system is dependent on local servers.
Sandborn et al.	2021	Cyber-physical systems, Manufacturing, Blockchain	Information tracking of parts to avoid counterfeiting of manufactured parts using impedance.	Authentication of part identity is performed using impendence. A low-cost alternative could be utilized in conjunction with blockchain.
Chen et al.	2020	Finance, Supply chain, Blockchain	Supply chain financing of manufacturing SMEs using Bitcoin, public blockchain. The study focused on blockchain workflows towards improving financing SMEs.	The blockchain workflow did not highlight the underlying computing architecture.
Bellavista et al.	2021	Blockchain, Supply chain	Cross chain attacks whilst performing transactions of blockchain-based supply chain.	The system is software-based.
Sorger et al.	2021	Big data, Supply chain, Industry 4.0	Database management and backend to perform machine learning in a supply chain value network.	Database management to realize value-driven supply chain.
Zhang et al.	2021	Cloud manufacturing, Blockchain	Public blockchain using cyber computing resources.	Sustainable blockchain practices for consensus mechanism.
Wang et al.	2021	Advanced planning system, cloud-based, scheduling	Cloud-based advanced planning system and scheduling for SMEs in manufacturing sector, that is software-based and uses simulation to monitor processes.	System could integrate other technologies, like blockchain. System can be designed for real-time monitoring.

The study of related works brings forth the following questions regarding the development of a robust IS.

RQ1: What are the sustainable practices in a decentralized manufacturing SC?

RQ2: Considerations for industry 5.0 and how manufacturing SCs can be integral for industry 5.0?

RQ3: How CM adoption optimizes SC efficiency?

RQ4: How to optimize and integrate CM and blockchain for seamless operations cost-efficiently and -effectively?

RQ5: How to remove technological constraints for SMEs, so they can tap into industry 4.0 effectively?

2.1. SCM for Railcar Manufacturing Enterprise

A railcar manufacturing enterprise is a large ecosystem of interconnected processes and systems for the manufacture of a railcar. The railcar manufacturer conducts its supply chain in a controlled environment, outsourcing mainly from SMEs. A pull style is the operation strategy that exists between the manufacturing enterprise and its suppliers. The transport manufacturing industry has a hierarchical supply chain structure [34] for assembling the railcar through various suppliers. In addition, the manufacturer maintains a customer demand–order coordinated system for assembling the railcar, whereby it dictates downstream activities to its suppliers. As such, a timely updated transactional record is essential for execution in the supply chain [35], where transparency is enhanced through the adoption of blockchain technologies.

Manufacturing is becoming more intelligent, integrated, and complex, whereby processes undertaken require data capture and documentation [11], as highlighted in Figure 1 below.

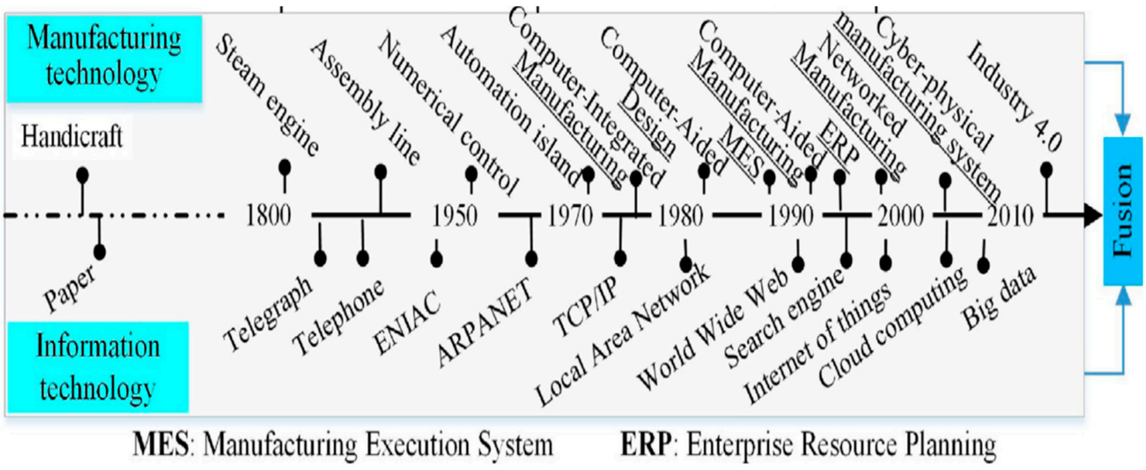

Figure 1. Illustration of changes in manufacturing and information with time [36].

An information value flow is developed by integrating vertical and horizontal operations of the SCM, by merging operational data such as order details, and the supplier's technical data such as machine, process, and product data [37]. Technology advancements such as BD and the IIoT allow SC access to internal and external data, such as sales, procurement, production details, etc. [38]. CM presents an opportunity to deploy a cloud-based advanced planning system (APS), as opposed to investing in server-based APS software [39].

In the transport manufacturing industry, part manufacturing is performed using discrete manufacturing. The scheduling of jobs in CM is a complex process, which is resolved through mapping tasks and distributing amongst SMEs, for the optimal provisioning, readiness, and availability of parts [40]. Decisions, processes, and activities for manufacturing low-volume high-variety parts are highly co-dependent, whereby material handling greatly affects a manufacturing system's productivity, profitability, and flexibility [41]. CM pools virtualized manufacturing resources from distributed manufacturing suppliers, whereby the scheduling of these resources in real time is an emerging research interest, as complex manufacturing projects present precedence constraints to distributed and heterogenous manufacturing resources [42].

The private blockchain permit sharing of smart contracts [43] enables the sharing of manufacturing specifications in a collaborative manufacturing environment. Yuan et al. [44] highlighted that innovations in SC are two-fold, i.e., improved efficiency resulting in increased communication speed and effective SC networks. Chen et al. [45] identified that a big drawback of SC information systems in the auto retail industry is poor trust amongst manufacturers, suppliers, funding organizations, etc., as records are susceptible to tempering. Due to poor trust amongst participants, the railcar manufacturer employs authentication processes which are time-consuming and costly for the verification of the details of produced parts at warehouse intake.

2.2. Industry 4.0 and Sustainability

"Blockchain is a next-generation development of information technology for realizing sustainability in businesses and industries" [46]. The success of the Sustainable Development Goals (SDGs) is dependent on solving the nexus challenges of economic development and sustainable development [47]. The integration of industry 4.0 technologies has resulted in a paradigm shift from traditional manufacturing models, whereby industry 4.0 is an expeditor of the adoption and implementation of SDGs by SMEs [48]. The digitization and sustainability convergence remains underdeveloped, yet industry 4.0 is an enabler of sustainable development [49]. Sustainable performance cannot be realized without innovations; therefore, industry 4.0 emerging technologies will drive development towards the quick realization of SDG targets, especially in economic development [50].

To develop sustainable solutions, it is noteworthy that each system revolves around digital value creation [49]. Blockchain is a pervasive technology in information systems, where transparency, immutability, and real-time operations address various sustainability challenges [51]. As such, product traceability has become a differentiator in the supply chain industry of high-value goods, as well as its application to trace that resource materials are environmentally sourced and not causing harm further downstream [26]. The application of a quick response (QR) code for product traceability reduces the need for paper invoicing and job cards, which results in reduced forest deforestation.

2.3. Big Data and Cloud Manufacturing

Supply chains generate a lot of information that needs to be traced and undergo multiple authentications for product delivery. The manufacturer uses an electronic ERP system and uses paper job cards to record production work on the shop floor and trace assembly parts on the assembly line. A complex network is created in tracing parts, assembly processes, and suppliers within a railcar manufacturing enterprise, which is not spared from errors during data capture and the sharing of manufacturing specifications with purchase orders to suppliers. Therefore, information asymmetry in SCM needs to be eliminated as information flow is the core of operations in a supply chain network [4].

Smart manufacturing is being managed by information systems and manufacturing data have become intelligent and valuable [36]. CC research has mainly focused on technological issues, whereas research on enterprise management has gained little traction [3]. The creation of new business models for cloud manufacturing has been identified as a research gap, as manufacturing has changed from being fixed in the same location to incorporating the new opportunities presented by digitization [13]. As such, DevOps, i.e., the integration of software development and operations powers industry 4.0 towards the synergy and interconnectedness of the value chain, is presenting new opportunities and infinite possibilities for value creation [52]. Based on findings by Wassem, Liang, and Shahin [53], organizations are adopting MSA for different purposes such as agility (82%), performance improvement (57%), and scalability (78%), with DevOps influencing the implementation of MSA by (47%). Scalability is a crucial aspect for consideration in SCM, as the influx of orders is always fluctuating. The open serverless framework, OpenFaaS, allows developers to build serverless functions based on defined and created templates of different languages and is reliant on Kubernetes (K8s) to provide failover and high availability management [20].

Microservices permit incremental modernization to achieve highly scalable systems, which are adaptable for both large enterprises and SMEs, whilst reducing the system redundancy of service instances at a low cost [54]. DDD offers guidelines for the domain decomposition of a business to identify principles, patterns, and practices [55]. The acquisition of boxed flat sheet metal parts is a subsystem of the assembling process, hence the cloud system is designed for flexibility as suppliers change with time. Scaling in cloud-native applications permits parallelism and concurrent use by multiple users seamlessly without disrupting production activities [56]. Microservices are ideal for cloud-native applications, as each microservice is independently deployed and encapsulated, making them failure-proof to failure in the system, a characteristic that improves the service availability of applications [57]. Communication between microservices is performed using the representational state transfer application (REST API), which is executed by an event [56].

2.3.1. Challenges Encountered in Adoption of New Technologies by SMEs

Nayak and Dhaigude [58] identified the need to integrate sustainability and attain a triple bottom line in modifying SCM, although it presents challenges for SMEs. SME sustainability in the industry is affected by capital investments, mainly technological and equipment, which affects their ability to streamline operations [59]. By supporting industries to large manufacturing enterprises, SMEs contribute significantly to the economy through employment. Poor information asymmetry and the small scale of their business often affect SMEs' capability to access bank loans for equipping their manufacturing facilities [60]. Blockchain is expected to assist SMEs in attracting investment and financing, as it allows for the sharing of tax compliance forms in real time.

SMEs have been instrumental in the realization of economic and sustainable development goals (SDGs) through industrial and technological development by fostering innovation [48]. Bellavista et al. [61] identified that SMEs in manufacturing have already adopted advanced and automated solutions, however, these enterprises are not prepared for a fully interconnected industry. SMEs within the manufacturing SC face financial challenges in financing their endeavours, which negatively affect the production efficiency of the manufacturer [62]. In addition, financial constraints have led to the poor adoption of new technologies by SMEs and poor enterprise production technologies [62]. To effectively implement a CM system between the manufacturer and suppliers, the manufacturer equips each supplier with a cloud-based digital twin (DT) shear guillotine and press bending machine through leasing. Manufacturing specifications are shared with the DT based on resource scheduling and the APS of the railcar manufacturer. The adoption of blockchain into the SC improves transparency amongst trading partners and gives ease of access to lending institutions.

2.3.2. Serverless Computing

The migration of enterprises from monolithic architectures to containers and microservices has resulted in the prominence of serverless computing for the deployment of cloud applications compelling cloud applications [18]. The Cloud Native Computing Foundation defines "cloud-native as a new computing paradigm in which applications are built based on a microservice architecture, packaged as containers and dynamically scheduled and managed by an orchestrator" [63]. Two technologies emerged in 1950 that have shaped the computing evolution, i.e., containerization in shipping and time-sharing in computing, which brought automation and multitenancy, respectively [21]. Serverless computing, aka serverless, is the latest generation of the cloud computing evolution, which is a combination of function as a service (FaaS) and backend as a service (BaaS) [64], as shown in Figure 2 below.

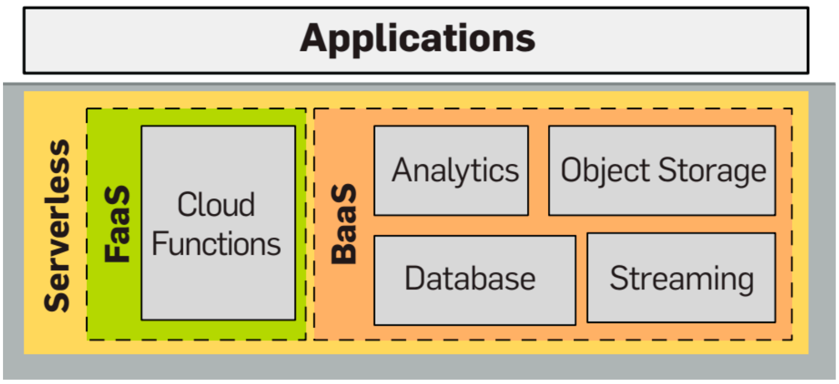

Figure 2. Illustration of application-specific serverless computing [65].

FaaS is an event-driven architecture with auto scalability properties, making it different from SaaS through virtual independence from underlying servers [20]. Developers create applications using high-level abstraction in serverless computing [65]. Serverless is thus best suited for high-performance computing (HPC) [66], making it applicable to the IIoT. Serverless has millisecond granularity for its pay-as-you-go billing model, offering two-fold saving benefits to companies. Serverless removes the need to perform backend administration to the server, making it affordable to pay for resources as it is based on a consumption-based model [66].

2.4. Permissioned Blockchain in Supply Chains

SCM is the crux of all organizational operations, giving transactional insights into procurement, sales, financing, and inventory management. The immutability and timestamping of heterogeneous data are fundamental attributes of blockchains, which make them ideal for organizational interconnection in industry 4.0 [67]. Blockchain enables direct transference of value amongst its multiple users securely [27]. Blockchain technology is transforming various aspects of SCM through peer-to-peer (P2P) networks and smart contracts to perform transactions for multiple suppliers [68]. A Hyperledger Fabric ledger consists of two sub-systems of the ledger, i.e., world state and transaction log [69]. Inventory management is thus performed through analysis of the world state database, using machine learning (ML).

Decentralization in blockchain removes intermediary costs whilst improving information security [70]. Blockchain application in SCM is expected to enhance the audit process through enhancing audit reliability, as the invoicing and authentication of transactions will be conducted in real time [32]. To date, most part tracing and inventory management is conducted using a traditional ERP system composed of both electronic and paper, a time-consuming process, as traceability includes part specification, supplier, modifications, maintenance details, etc., [71]. Faccia and Petratos [72] successfully integrated blockchain into an accounting information system (AIS) and ERP at multiple levels for audit compliance.

Karakas et al. [73] identified that there still exist gaps within the blockchain and SC integration, which has been attributed to the poor adoption of blockchain by organizations, as they lack sufficient knowledge on how blockchain is value adding to their business operations. Helo and Hao [74] highlighted that the integration of IoTs and blockchain is highly applicable in the SC to increase the transparency, accessibility, and effectiveness of SCs. Offering complex serverless architecture enables FaaS to interact with tables hosted on not-only structured query language (NoSQL) databases [75]. This workflow illustrates the integration of cloud manufacturing and blockchain, whereby each task is event-based and is initiated by a trigger. Data encryption in blockchain prevents data tempering whilst improving the system security of the CM system [12], making transactions within the SC, and CM authentic through use of smart contracts.

3. Methodology

To realize the full potential of i4.0 in supply chains, all enterprises must be able to interact with other organizations [76]. A hierarchical supply chain structure is utilized for the production of railcars, as illustrated in Figure 3 below. Through the ERP system, the manufacturer possesses an inventory database of all parts used for railcar manufacturing, which are coded based on their functionality and a pool of its suppliers. It begins the supplier selection process which is dependent on variables attained from supplier audits such as the ability to deliver on time, lead times, manufacturing capacity, etc. The suppliers, comprising various SMEs, are issued with a purchase order of parts to manufacture by the railcar manufacturer through the procurement office accordingly, along with the design specifications of each part required. Subsequently, for flat sheet boxed metal parts, the suppliers then determine their own process sequence for production.

Various parts are produced by various suppliers, which may also include the same parts and/or part families. Production techniques such as batch production, just-in-time, and flow production are utilized by the suppliers for part production. The order quantities differ, subject to an SME's supply capability as a result of machine availability and input materials. Parts are then supplied to the manufacturer, who performs quality control upon receiving the parts, and the identification of respective parts. Part tracing is implemented at warehouse intake, however, rejected defects are sent for rework to the initial supplier or are sent to another client, if the contract is terminated. The parts are then put onto the production line for assembly or stored temporarily in the warehouse.

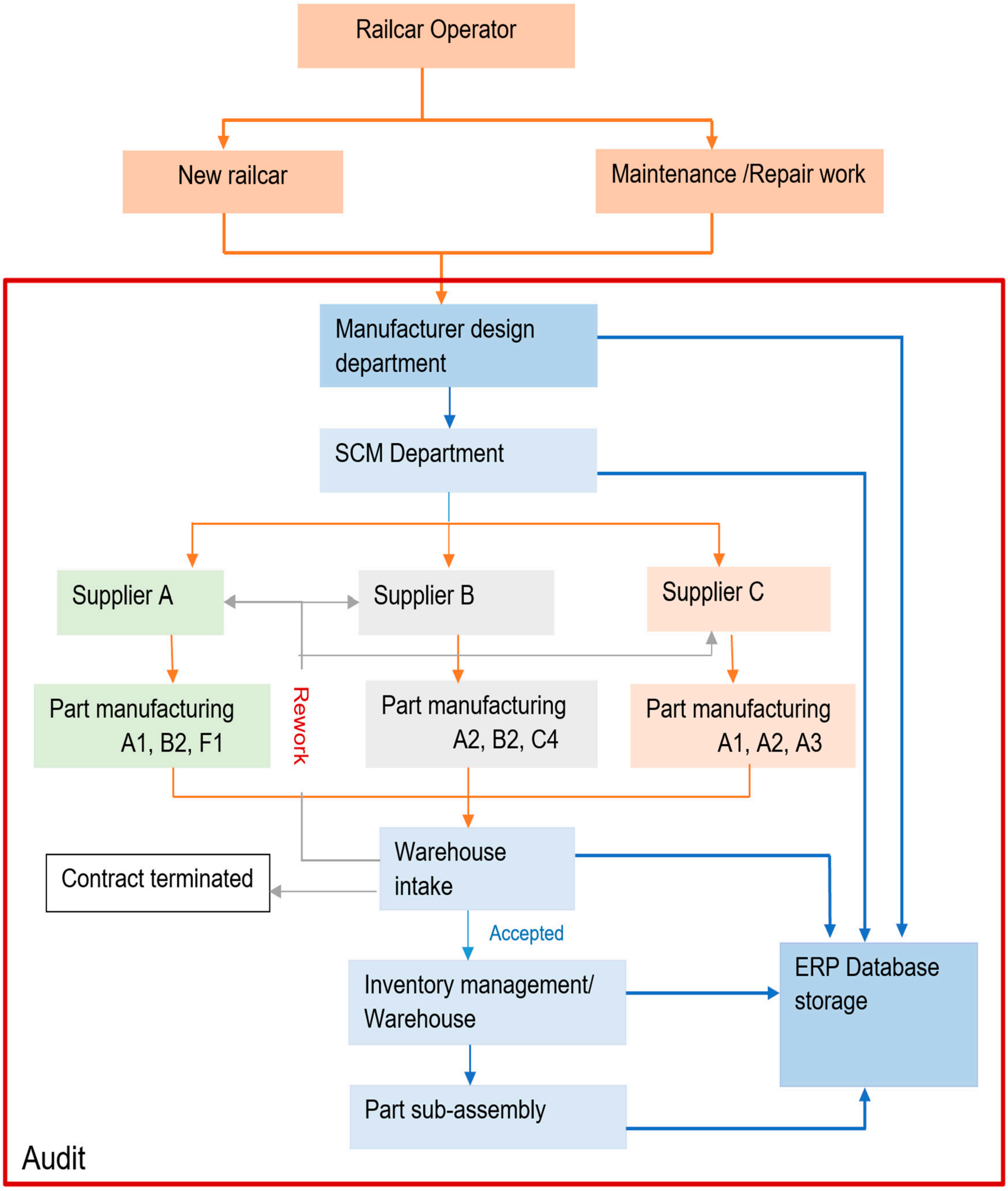

Figure 3. SCM process for railcar manufacturing of boxed flat sheet parts for railcar assembly.

SCM affects all aspects of an organization, therefore, a systems engineering approach was applied for both vertical and horizontal integration. The exchange of information is taxing for both the manufacturer, supplier, and auditors as information is captured multiple times by the stakeholders, is fragmented, and different information systems are utilized. Information management is the core of operations management, hence information links based on engineering, SCM, and accounting departments are realized within the system. A new business model is required for integrating IT with lean manufacturing systems to avoid non-value-adding processes during systems development [77]. Bai and Sarkis [51] identified that the technology evaluation by most organizations is based on traditional financial metrics. Therefore, from the supply chain process currently being conducted by the manufacturer, challenges are identified as shown in Figure 4 below.

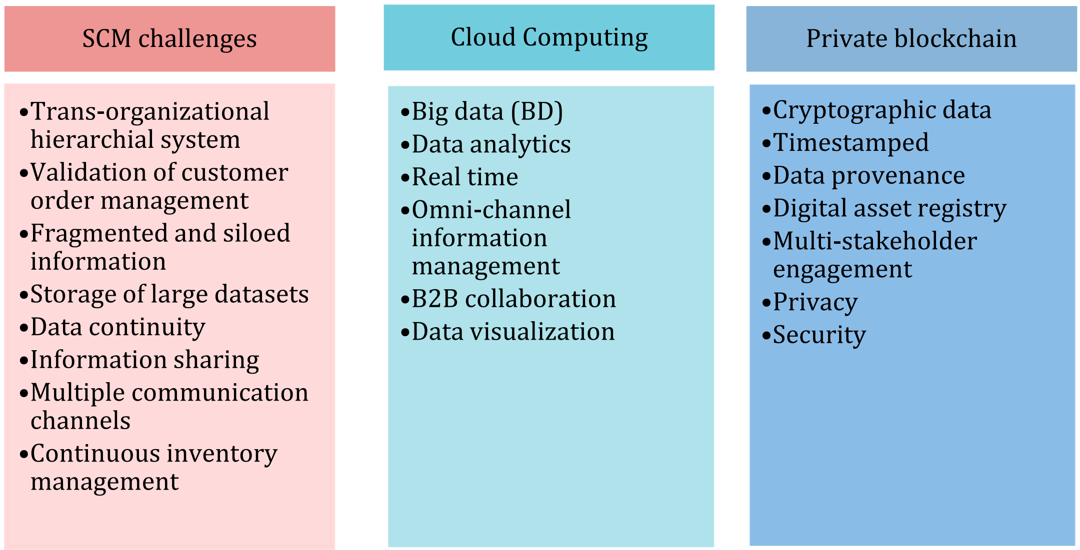

Figure 4. SCM constraints and new enabling technologies for transformation.

According to Helo and Hao [78], the adoption of CC establishes linkages between ERP, manufacturing resource planning (MRP), and customer relationship management (CRM), which when merged with engineering design and manufacturing, result in a cloud manufacturing supply chain system. Since multi-stakeholders with different roles interact within the system, an information systems management with different cloud identity access administration roles is suggested. To further reinforce the cloud manufacturing supply chain system, blockchain technology is integrated into the cloud manufacturing system. Blockchain has the advantage of knitting various stakeholders whilst maintaining privacy and immutability [33]. Henceforth, merging blockchain, cloud manufacturing, and SCM in a manufacturing enterprise results in an integrated IT and OT management system for the manufacturing of railcars.

Multi-criteria decision-making (MCDM) was used in the selection of cloud resources, a cloud service provider, and blockchain API. Microsoft Azure and Hyperledger Fabric, an open-source enterprise-permissioned ledger [69], were selected as the cloud service provider and distributed ledger, respectively. Data are stored in a chronological structure through the chaincode, allowing the tracing of transactions within the organization. The manufacturer requires an up-to-date inventory list of parts in the warehouse and the production line, as such parts need to be identified and quantified. Part provenance becomes crucial to identifying produced parts and in performing reliability-centred maintenance (RCM).

Various tracking devices have been adopted for tracking different goods, such as barcodes, physical markings, job cards, radio-frequency identification (RFID) tags, QR codes, etc., in various manufacturing, distribution, and warehouse environments. A QR code was selected, as it allows for 3D data capture and storage, which can easily be scanned and/or produced for part tracking along the assembly line. In contrast, a barcode only allows a limited number of coded numbers and letters to ascribe processes that a product has undertaken. RFIDs are quite expensive and cumbersome as they need to be changed at every sub-assembly. However, the QR has the advantage of taking a small proportional area in relation to data storage.

4. Development of Blockchain-Based Cloud Manufacturing System

Technologies shaping Factories of the Future are impactful, especially in comparison to work design processes, with the growing realization that human–machine symbiosis adds value to industry [79]. Thus, it becomes necessary not only to employ i4.0 technologies for digitizing processes but also to improve the working conditions for employees. SCs information systems are error-prone, as they are highly dependent on employees for data capture and recording, leading to poor data integrity. Blockchain reasserts value exchange within the IS, whilst improving procedural management and cost control [45].

4.1. Blockchain and Cloud Manufacturing for SCM

The move from on-premise data centres to cloud services has created a plethora of opportunities for collaboration in business and new sustainable value creation through digitization. Utilizing serverless computing, a multiple provider-managed cloud service offering triggered by events is deployed [75]. Therefore, cloud services for the manufacturer are built on K8s, which is a platform for large enterprise applications, to allow for multiple container orchestration. There are no execution costs in a permissioned ledger [80], making it favourable for use amongst SMEs. The Hyperledger Fabric is built on a Kubernetes platform. Both systems are built for enterprise applications and are open-source and modular architectures.

An AIS is centralized as it is the core module of business operations, integrating multiple applications to perform various business processes, and hence the AIS system design and analysis is arduous [72]. Consequently, a permissioned blockchain with centralized authority was adopted for hierarchical SCM. Blockchain is event-driven due to its asynchronous characteristics, as latency is incurred whilst awaiting confirmation of transactions [81]. K8s' command line interface kubectl is used to run commands and orchestrate resources. The microservices are deployed onto a pod, which is the smallest executable unit in K8s. The pod encapsulates the loosely coupled microservices to operate as a single unit with a shared IP address. K8s has different controllers, however, in this study, StatefulSets controllers were utilized for stateful pods [82]. Statefulness is critical in SCM systems, as pods are ephemeral and data need to be traced along the IS.

The supply chain is built around a hierarchical information system interface through identity management access. Fabric is a permissioned DLT with pluggable consensus mechanisms [69], enabling information sharing whilst maintaining privacy amongst multi-stakeholders, which can easily be revoked dependent on supplier performance. In a manufacturing enterprise, product specifications include CAD files, material information, invoices, etc., which are shared as smart contracts with the supplier. Since the manufacturer has multiple suppliers for its multiple components and parts, it offers various contract conditions to its supplier based on its discretion. The channels create ledgers inside ledgers, which are private to other peers within the network, allowing for private communication [69]. As such, multiple channels are created and interlinked between various departments and suppliers, which are also private to other participants based on their identity and role.

Fabric uses an execute-order-validate architecture [69] in its transactions. As such, the parallel execution of multiple transactions occurs within Fabric concurrently and are shared across related multiple collections. A chaincode is created once a transaction has been accepted and is used in tracing transactions that occur within Fabric. Since the world state is immutable, records are stored in the ledger, which consists of various aspects of transactional and supply chain documentation. The world state database is shared with an external party, an auditing firm to perform an audit of the financial transactions and inventory of stock, that occur during an annual year.

4.2. Supply Chain Analytics

One of the facets which have led to the rapid adoption of industry 4.0 technology is BD. A digital asset registry of parts, components, and suppliers is created using Fabric, which streamlines and updates inventory based on part (re)manufacture for the railcar. The digital asset registry continuously updates based on input data from a procurement official. CouchDB is selected as a state database for the ledger, which is accessible off-chain and is pluggable. Chaincode is deployed on K8s as an external service provider [69], which can be queried and indexed since it is a NoSQL customizable database written using JavaScript oriented notation (JSON). Fabric software development kit (SDK) framework permits pluggable API to chaincode, where python is plugged to conduct ML. Metadata on the state database are cryptographic and timestamped across the value chain, with multichannel identity access, etc., which creates a rich data warehouse for analytics and AI [83].

CouchDB is indexed and queried based on SC data written on the database, such as a unique ID/ primary key. The querying of data attributes such as part_id, supplier_id, railcar_id, date-of-manufacturer, sub_assembly, part family, and railcar_id, allows for inventory management. Composite keys, i.e., double or triple data attributes, can be used to query composite data such as supplier_id and product_id, part-class, etc., for inventory management. Python allows the parallel execution of processes, and as such, multiple queries can be conducted by multiple peers based on their identity. Fabric has the capability to perform 2000 transactions, and in a private blockchain with limited use, the system is not overwhelmed.

4.3. Part Assembly Tracking

The assembly of a railcar follows a structured production process and therefore a QR code identification system is adopted, permitting information flow and continuous updating from the beginning to the end of the process. A railcar is manufactured with thousands of parts, hence a QR code is more applicable in comparison to an RFID, as it is sizeable and stores multiple details about a product. The QR code can easily be labelled using cryptographic and timestamped data for record-keeping based on the Fabric data, which ensures accuracy in data capture. QR codes are easily printed onto a part and/or scanned thereon, hence parts are traceable along the assembly system. This process can be applied across the manufacturer’s assembly plant for various sub-assemblies for part tracing and during RCM.

Each manufacturing machine possesses a unique serial number which is utilized for its identification. As such, as a supplier is awarded parts for manufacturing, the cloud manufacturing “event” is triggered to start the manufacturing process, which is controlled through resource scheduling. The blockchain system uses the IS network to control and monitor the SCM processes, suppliers, and manufacturing process, hence it is able to trace each manufactured part incrementally. As each part is produced, it is stamped with a unique QR code based on a supplier’s details, namely, the supplier, the machine, and the type of material used. Timestamping is used in determining the exact date a part is manufactured, which is critical for life cycle analysis (LCA).

A challenge often encountered by the manufacturer is the production of parts with different materials for part manufacture. As such, inventory management using deep learning (DL) algorithms such as neural networks, were applied in order to forecast other aspects of the SC such as part failure. DL application to identifies how the varying materials perform in operation. DL is also used to simulate and optimize assembly processes by mapping them to cloud-based scheduling and planning. Lastly, the application of data analytics within the system allows for visualizations, which are used to identify supplier performance and manufacturer productivity.

5. Results

SC data are continuous although generated from discrete data. A multi-tier centralized system was developed on Microsoft Azure, which reflects the hierarchical production nature of the manufacturer’s supply chain. A systems engineering approach was applied to identify the interplay that exists between systems within the multi-hierarchical relationships amongst stakeholders. DDD was applied to develop an agile and modular SCM system, whereby departmental operations are built onto a microservice based on functionality. Since this is a tracing system, stateful microservices are applied. Each microservice is built with a database attached, and communication within the channels is event-driven, as illustrated in Figure 5 below.

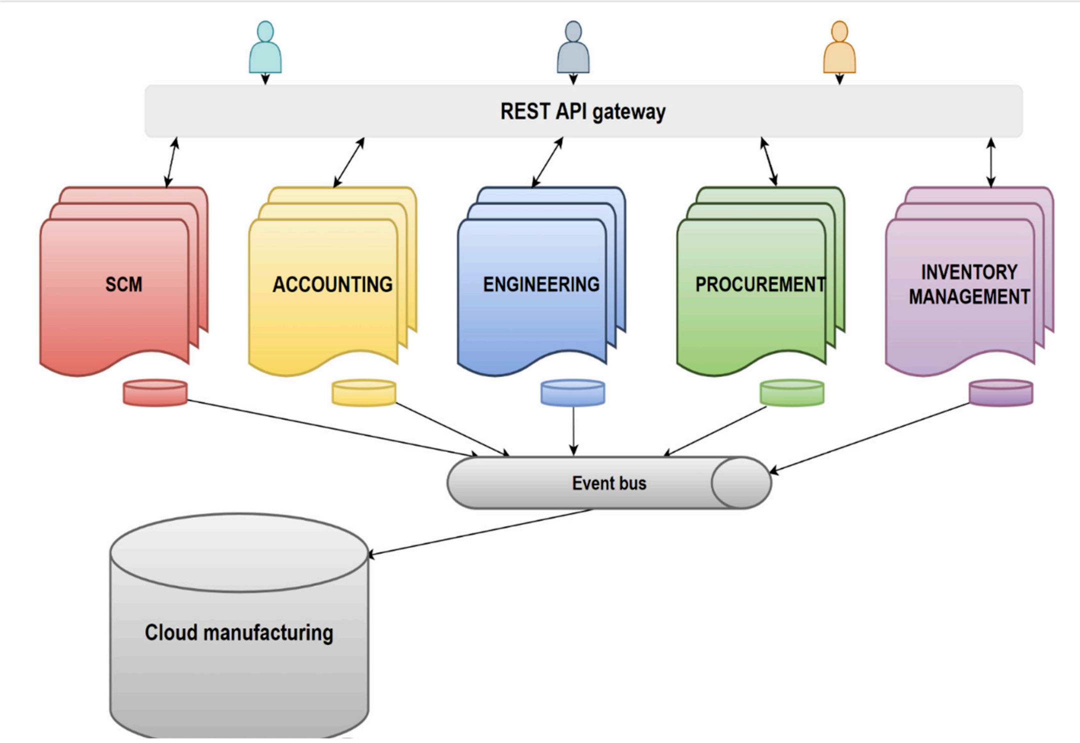

Figure 5. BCMaaS and SCM system architecture for boxed sheet metal manufacturing.

The microservices are deployed independently onto a K8s pod, resulting in a K8s cluster for the system. K8s offers a container orchestration platform, enabling an integrated vertical and horizontal SC orchestration, for inter-organization and intra-organization multi-level auto-scaling systems. A consumption-based payment model for cloud resources is a cost-efficient pricing model, especially for SMEs, due to the high capital expenditure in acquiring a local server, administration, and maintenance

A blockchain-based SCM system was built on Fabric and deployed on K8s for easy container orchestration. A DT is deployed as a container under the microservice for engineering, whereby manufacturing specifications are shared within the IS using a smart contract, within select suppliers, and using a channel. CouchDB was selected as the default world state database. A private ledger was designed for permissioned multi-tier levels of access and authority. The Fabric network is centralized, based on the AIS system, to enable the tracing of material, information, and money flow within the environment. Chaincode is a centralized repository of information, based on an execute-order-validate ordering system across multiple channels. Multiple smart contracts are interlinked within the chaincode for data traceability for financial transactions and audit reliability. To further strengthen the system, a QR label is autogenerated by the BCMaaS system and is inscribed onto each produced boxed sheet metal part. This process creates an automated inventory management system for part production. Since the assembly process for railcars is defined, the master chaincode is continuously updated to trace the assembly process by the railcar manufacturer. CouchDB is queried using complex queries in order to identify different attributes such as inventory stock, production dates, purchase orders, etc. ML is applied to metadata to give supply chain analytics and give foresight on matching production activities to assembly. As such, the system allows for a supplier performance audit, inventory analysis, the optimization of the assembly process, and the forecasting of part supply and part requirements for maintenance activities.

6. Discussion

Industry 4.0 technologies are changing the processes in the business ecosystem, whereby the computing evolution is taking centre stage, as a medium enabling the dynamic changes. Therefore, it becomes essential to develop industrial operations based on DevOps. Serverless computing enables omnichannel operation, hence it can be accessed anywhere in the world by various participants who have access to the data based on identity access management. Consequently, the convergence of digital technologies on serverless improves digital interoperability in a collaborative manufacturing environment amongst multiple stakeholders. Event-based microservices alongside smart contracts inhibit the progression of data collection and processing if a transaction is incomplete and is simultaneously flagged for fraud. Part and order provenance is enabled by AI-augmented blockchain analytics, which queries CouchDB to give metrics on supplier performance and reliability. At the operational level, the developed system performs cloud monitoring of available resources, so that orders are issued based on key performance indicators, such as the availability of machinery, raw metal-flat metal sheets, daily working shifts, delivery times, etc., of manufacturing suppliers. In addition, the BCMaaS system nears zero defects and reduces operational deficiencies in SCM, such as incorrect data capture and duplicated documents, preventing metadata manipulation, tracing changes to records, etc. The BCMaaS system performs real-time ordering and monitoring of tasks to identify idle and poorly performing machinery and suppliers, in order to remap resource scheduling based on current system constraints. The remapping of resources ensures that the railcar manufacturer produces a railcar with limited downtime and meets set targets for the delivery of the railcar. Subsequently, the railcar manufacturer benefits from digital forensics, performed to identify value systems within the (re)manufacturing of railcars. The plugin architecture of BCMaaS allows for easy plug and play into upstream supply chain operations for part integrity and identification. Furthermore, the system can be extrapolated downstream of the value chain for sheet metal suppliers.

The application of blockchain in the supply chain is set to improve quality control in the manufacturing environment, lower overhead costs, and share data securely. The BCMaaS system improves data validation whilst reducing audit deficiencies resulting from insufficient information, as the system is accessed and processed in real time across the value chain. Supply chain analytics give an insight into reliability-centred maintenance, as metadata from railcar re-manufacturing show parts that are continuously replaced. Supplier information, inventory management, and accounting details are shared with an audit company to perform a real-time audit and transaction authentication, tracing, and validation as Fabric ledgers are immutable. The chaincode can be analyzed by auditors in search of transactional ambiguity and fraudulent activities within the enterprise SCM system. It is also used to determine audit reliability seamlessly. Part traceability in real time using a blockchain-based QR code reduces the need for paper invoicing and job cards. Performing work in real time prevents in-person travelling, especially for auditors, to authenticate documents and inventory stock, leading to a reduction in carbon footprint as audit reliability is performed in real time. Future work should focus on a multi-cloud seamless approach for collaborative enterprise management, whereby enterprise IS built on different clouds are able to handle synchronous workloads. This is critical in a digital economy with multiple manufacturers and multiple suppliers, who need to interact regardless of being hosted by different cloud service providers. Further research still needs to be conducted on the cyber security of IIoT systems for the prevention of malware sharing in machine-to-machine systems.

7. Conclusions

BCMaaS is a serverless function whose abstraction is cloud-native, with information systems being the backbone of business operations. The system incorporates new age technologies, namely serverless computing, CM, ML, etc., to manufacture at source and offset the carbon footprint. The convergence of digital technologies enables effective multi-tier collaboration in a digital ecosystem seamlessly. An agile hierarchical supply chain framework is applied for the ledger, utilizing lead times in product planning and development to optimize business-to-business (B2B) collaboration through intelligent assets. Blockchain has multiple applications in supply chains, which introduce new value whilst enhancing an organization's efficiency and productivity. The benefits of cloud manufacturing are further strengthened by merging it with blockchain in a supply value chain. Various aspects of SCs are being transformed, therefore a radical approach is required in SCM, instead of silo upgrades for organizations to fully realize the benefits of blockchain. Through the collaboration of stakeholders and the exclusion of intermediaries, new business models are being established that result in new value chains, whilst omitting third-party costs. As such adoption of blockchain technologies is a win-win for both manufacturers and SMEs, it improves B2B relationships through privacy and collaboration. The systems' plugin architecture permits multi-cloud deployment to enhance flexibility for the orderer organizations, and SMEs can easily plug into the ecosystem. Therefore, the BCMaaS easily system integrates into i5.0, where the system improves hyperconnectivity between enterprises whilst improving the working conditions of employees.

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