Traceable and Intelligent Supply Chain based on Blockchain and Artificial Intelligence

Sachin Karadgi, Vadiraj Kulkarni, and Shridhar Doddamani
KLE Technological University, BVB Campus, Hubballi – 580031, INdia

E-mail Sachin.Karadgi@kletech.ac.in

Abstract. Smart manufacturing focuses on maximizing the capabilities to increase multiple objectives, like cost, delivery, and quality, in manufacturing enterprises. This requires implementing product development lifecycle, production system lifecycle, and business cycle for supply chain management. In short, a considerable amount of data is generated in a given manufacturing enterprise. Likewise, progress has been made to adopt blockchain in financial industries, but the adoption is slow in non-financial sectors. The article elaborates a methodology for the realization of a traceable and intelligent supply chain. First, the methodology elaborates on the realization of traceability of enterprise entities, which are an integral part of the supply chain. In this case, each participating stakeholder of the supply chain is required internally to realize a smart manufacturing system with an extension to write critical control data to the blockchain (i.e., a subset of process data). Artificial Intelligence (AI) is being adopted in most industries. A supply chain stakeholder has access to its data and can employ AI to derive new insights. The data available with the stakeholder provides a narrow context. With blockchain, all the stakeholders have access to the data from other stakeholders. Subsequently, the insights derived by a stakeholder will be more meaningful. This will assist in realizing an intelligent supply chain.

1. Introduction
In today’s age, it is possible to realize Industry 4.0 as enormous progress has been made in the area of embedded systems, cloud computing, smart devices, and most importantly, Cyber-Physical Systems (CPS) [1, 2]). Additionally, it is possible to address the smart objects uniquely with the introduction of the internet protocol IPv6 in 2012, leading to the creation of the Internet of Things (IoT) [1]. This has positively impacted manufacturing and can be described as the fourth stage of industrialization or Industry 4.0 [1].

Industry 4.0 focuses on data and insights derived from this data. Data is indispensable to integrate the existing information technologies within an enterprise and across the enterprise boundaries leading to the implementations of horizontal integration through value networks, end-to-end digital integration of engineering across the entire value chain, and vertical integration and networked manufacturing systems [1].

Likewise, smart manufacturing focuses on maximizing the capabilities to increase multiple objectives, like cost, delivery, and quality, in manufacturing enterprises [3]. This requires implementing product development lifecycle, production system lifecycle, and business cycle for supply chain management [3, 4]. Subsequently, a considerable amount of data is generated in a given manufacturing enterprise.
Industry 4.0 and smart manufacturing stress the importance of end-to-end digital integration of engineering across the product’s value chain and horizontal integration through value networks. This integration throws difficult questions, like trust between collaborating enterprises, information to be exchanged, protection of intellectual property and data, and securing products, resources, and processes, among others [5, 6, 7]. These are true for any manufacturing enterprise but crucial for highly regulated manufacturing enterprises, like pharmaceuticals.

As mentioned earlier, a vast amount of data is stored in the local database, which supports efficiently conducting its day-to-day business. This data can be used to derive valuable insights by employing Artificial Intelligence / Machine Learning (AI/ML) algorithms and enhancing the employed processes’ efficiency and effectiveness. However, the downside is that the data is particular to that stakeholder of the supply chain in question. For instance, a tier-1 supplier would have no idea how the manufacturer uses its products or components, i.e., lack feedback or have a narrow context of processes. Thereby, this reduces the opportunity to derive insights with a broader context and lacks in process improvement initiatives.

This article aims to present concepts to realize the seamless exchange of information across enterprise boundaries by exploiting blockchain and subsequently employing AI/ML algorithms to derive new insights. The article is organized as follows. Section 2 presents a literature review on blockchain and AI/ML and their applications in the manufacturing domain. Next, a methodology is elaborated to integrate blockchain as part of smart manufacturing systems in Section 3. The article concludes with a discussion on the challenges in adopting blockchain in the manufacturing domain in Section 4.

2. Literature Review

Information needs to be exchanged at enterprise boundaries but is not straightforward. A manufacturing enterprise needs information (e.g., quality) about the incoming raw materials or semi-finished products from suppliers. This will help achieve traceability and increase trust and reduce costs incurred due to retesting, among others. However, this information is difficult to get, and if there is any information, the chances of being manipulated are high. Similarly, this is true for the regulator, certifiers, and customers. Finally, there are questions about what information to be exchanged and how to be exchanged.

The introduction of bitcoin gave birth to blockchain technology [8]. Blockchain technology and distributed ledger have been attracting many industries, with financial institutions being the primary users of blockchain technology. An example of bitcoin and underlying blockchain in financial institutions to transfer money is depicted in Figure 1. Blockchain is a specific kind of database where the data (and underlying transactions) entered will be formed into blocks and linked to other blocks chronologically, as shown in Figure 2. The stored data (or transactions) is cryptographically signed and cannot be altered once written to the blockchain [9]. Blocks in a blockchain can be thought of as a page in a ledger book.

Transactions on a blockchain can be anything from sending and receiving the money to operations on a database [10]. Blockchain data is encoded in Merkle trees, which provide efficient and secure architecture to store the data. As soon as the transaction is submitted to the blockchain, the transaction has to be verified. Consensus algorithms are the way to get a joint agreement from the entire network to generate a new block. Two of the most popular algorithms are Proof of Work (PoW) and Proof of Stake (PoS) [8, 9].

PoW is an algorithm where it chooses the miner that generates the next block. PoW gives out a complex mathematical problem, which requires enormous computation power to solve. The miner who solves the problem first is chosen to create the next block and is rewarded accordingly. PoS is an algorithm wherein the validators or miners stake the network coins. Validators place a bet on a discovered block if it can be added to the network. Validators are chosen to create a next block based on their stake in the network. The validators are incentivized for their work.

There are two types of blockchain: public and private [11, 6]. Many blockchains are public so that anyone can verify the integrity of the data that is on the blockchain. Public blockchains are accessible to anyone that wants to join the network. Anyone with the blockchain’s source code or software can be
validators and are authorized to read and write to the blockchain. The system is entirely decentralized. The consensus mechanism for the public blockchain is permissionless [6]. Likewise, there exists a private or enterprise blockchain managed by selected entities. Private blockchains are used by organizations where the efficiency is high, and arriving at the consensus should be fast. The blockchain is not entirely decentralized. The consensus mechanism for this type of blockchain is permissioned, which means not everyone can read and write to the blockchain, nor can they be validators [6]. When comparing the permissioned and permissionless systems, the permissionless consensus protocols are much suited for the blockchain network and provide an efficient way for scalability.

![Diagram](image-url)

**Figure 1.** Working of bitcoin and underlying blockchain.

The blockchain network protocol can be broken down into four layers [9]: protocol of data and network organization, protocols of distributed consensus, a framework of autonomous organization based on distributed virtual machines (VMs, e.g., smart contracts [12]), and implementation of the interface for users to interact. The bottom layer is the data organization layer provides many unique functionalities to the node that uses cryptographic functionalities to secure the node [13]. In the early days of blockchain, the transactions were digitally signed and arbitrarily packed with some cryptographic functions so that the miners can identify if the transaction is being tampered with. This package is called a “block.” The blocks are arranged in chronological order forming a chain that becomes a “chain of blocks” and hence blockchain.
The network protocols provide an architecture where the nodes connect with each other in the network. A peer-peer network is formed where every participant has the same power as the peers. This protocol’s functions are to discover the peers, find the route to peers, and transmit encrypted data over the peer-peer network. The consensus protocol is the blockchain’s brain and heart, which provides and maintains consistency, chronological ordering, and integrity of the system. The consensus protocol provides Byzantine agreement in the network [8]. During choosing an accessed-control system, the blockchain networks often adopt Byzantine faulty tolerant consensus protocols. For example, practical Byzantine faulty tolerance is adopted to reach consensus in a small group of authenticated nodes [10]. This is for permissioned blockchain networks, and for permissionless blockchain, the consensus is achieved by a combination of techniques, including cryptographic zero knowledge and design where incentives are provided to the miners.

Smart contracts are programmatically written contracts that ensure the parties involved in a contract abide by the contract’s rules and conditions [12]. These contracts are deployed on blockchain and accessed by anyone on a public blockchain and the authorized users on a private blockchain. The smart contracts are implemented with confidence over the robustness of the consensus protocols. There is a distributed VM architecture where the smart contracts are implemented. The smart contract protocols are consistent even if the platform underneath varies. For example, they can be deployed in stateless circuits as Bitcoin and complete state machines such as Ethereum and Hyperledger Fabric. The VM layer enclosing the consensus, data, and network protocols is hidden away. The application layer is the only part of the application that is visible to the end-user. Many distributed applications are being created to help use the blockchain architecture to transact with cryptocurrencies.

Researchers have discussed employing blockchain to address the various issues of the supply chain involving multiple stakeholders and in numerous non-financial domains [7, 11, 14, 15, 16, 17, 18, 19]. NITI Aayog has stressed the importance of blockchain as a transformative force to support various operations, specifically from multiple stakeholders, like regulators, policymakers, and citizens [6]. NITI Aayog has discussed blockchain implementation in the pharmaceutical supply chain and claim verification and approval of fertilizer subsidy, among others [6]. This will improve profitability and quality, increase transparency, and reinvent products and processes [6]. Furthermore, a use case evaluation framework has been proposed. The current proposal has utilized this framework to arrive at the use of blockchain [6].

AI is used everywhere nowadays. It is the science of making computers think and make decisions like humans. ML is a sub-field of AI where the machines are taught to learn from inputs and predict them. Various algorithms are used to train a machine to predict by processing the data. Some of the common algorithms used are linear regression, naive Bayes, Support Vector Machine (SVM), K-nearest Neighbors (KNN), and so forth. Some other algorithms, such as Convolutional Neural Network (CNN), are commonly used for analyzing videos and images.
AI has helped optimize supply chain management [20]. Applications of AI in SCM are: it provides forecasting of demand based on previous data, helps in production as it offers better optimization in the processes, and building better teams, which includes robots and people working together. AI also provides insights and can predict better times for promotions and pricing of the product. With smart retailing using AI, the retailer can benefit from fewer wastages. Using video analysis and tracking unusable products can be discarded at the early stages. AI plays an important role in supply chain management.

3. Methodology
A supply chain involves various stakeholders (e.g., suppliers, manufacturers, regulators, certifiers), as depicted in Figure 3 [7, 11, 14], forming a virtual or extended enterprise. Each stakeholder might have its own priority to achieve its objectives. This might require implementing suitable services based on suitable AI/ML algorithms to achieve its objectives. This brings data into the foreground and involves the implementation of horizontal and vertical integration. The realization of horizontal integration is achieved by integrating various enterprise applications across the supply chain, which internally requires mainly addressing interoperability issues [1]. Likewise, the realization of vertical integration is achieved by integrating various applications across enterprise levels within and across enterprises, starting from sensors and actuators to enterprise applications (e.g., Enterprise Resource Planning (ERP) system) [1]. Furthermore, this requires addressing the temporal and semantics gaps among the different enterprise levels [21, 22].

A layered framework, very specific to a stakeholder (e.g., tier-1 supplier), is depicted in Figure 4 [23], which addresses the realization of horizontal integration and vertical integration within a stakeholder. The integration is as per the guidance of Industry 4.0 [1] and is based on IIoT’s three-tier architecture [24]. As mentioned, the layered framework is very specific to a particular stakeholder. This requires all stakeholders (except for regulators, certifiers, and so forth) to implement a system fulfilling their requirements based on a layered framework. The individual layers are briefly described in the following paragraphs [23].

- **Process Layer:** This layer denotes the processes (e.g., operations) employed by the enterprises to fulfill the customer requirements. It is crucial to model the processes and the underlying data models using various tools (e.g., Unified Modeling Language (UML), Entity Relationship Diagrams (ERDs)). Overall, the processes and model help carry out root cause analysis and support in building AI/ML models.

- **Resource Layer:** Resources are required to execute the previously defined processes. As part of smart manufacturing, most of the resources are automated systems with sensors and actuators. These sensors and actuators can send and receive data, respectively, utilizing various communication protocols (e.g., Profibus).

- **Edge Layer:** Data need to move seamlessly across the layers. The edge layer is responsible for establishing a connection with the resources located in the resource layer and databases in the data layer. Additionally, the edge layer implements different communication protocols to acquire data from sensors and dispatch control data to actuators, involving preprocessing to address interoperability issues.

- **Data Layer:** Data is crucial for downstream activities (e.g., performance computation). Hence, data need to be stored in databases hosted either locally or in the cloud. Apart from automation systems, data can also be acquired from other enterprise applications (e.g., ERP System).

- **Basic Function Layer:** The previously stored data might contain data islands. Hence, it is crucial to establish relationships between data islands through tracking and traceability functionalities [22, 25]. It is also required to compute numerous financial and non-financial (or operational) Key Performance Indicators (KPIs) to provide a comprehensive view of an enterprise. Likewise, numerous reports for the managers, line supervisors, and so forth can be generated.

- **Advanced Function Layer:** The functionalities required for managing the production, inventory, quality, and maintenance are encompassed in this layer. Here, the concerned operators are
involved with day-to-day operations with manual decision-making. It is also possible to introduce automated decision-making through the features of the Complex Event Processing (CEP) engine, which in turn addresses the temporal and semantic gaps of vertical integration [21, 26].

Figure 3. Different stakeholders supply chain [11].

- Smart Layer: Industry 4.0 focuses on data and insights derived from the data. The layers mentioned above provide the data with the necessary context. Advances in AI/ML algorithms have been made, which can be employed to derive new insights to solve various issues of an enterprise.
Figure 4. Layered framework to realize horizontal and vertical integration within a stakeholder of a supply chain [23].

Traceability plays a crucial role after the data acquisition as it tries to establish various relationships among enterprise entities (e.g., products, customer orders, production orders) [22, 25]. The relationships among enterprise entities are shown in Figure 5, adapted from [27, 28, 29]. These relationships assist in addressing isolated data islands and are the foundation for realizing functions of higher layers of the framework. For instance, perform efficient root cause analysis, support recall, and so forth. The Bill of Materials (BoM) and production routing are crucial to establish different traceability relationships apart from the process modeling. Traceability can be realized at different granularity levels that depend on numerous factors (e.g., product, production strategy) [27, 28].

A product or component that can be tagged uniquely through an identification will result in item-level traceability [27, 28]. This will assist in precise identification during root-cause analysis, product recall, and so on, but need to consider a high number of technical challenges during implementation. On the other hand, if the identical products or components are tagged uniquely through an identification, that will result in batch-level traceability [27, 28]. Here, the identical number can vary from few products to 1000s of products. The batch-level traceability can result in imprecise identification during root-cause analysis, product recall, and so forth, but with fewer technical challenges during implementation and high cost is incurred due to imprecise identification [28, 29]. Finally, there can be different types of traceable elements (e.g., trade units, logistic units) [30].

Irrespective of traceability granularity, it is necessary to generate unique identifications within an enterprise and across the enterprise. Here, there are few generic standards defined (e.g., GS1 and AIM).
In addition, there are industry-specific standards (e.g., IFRA for the pulp and paper industry). Traceability will be implemented as part of the basic function layer of the layered framework.

**Figure 5.** Entity-relationship diagram of enterprise entities [28, 29].

Events or any transactions, either manual or automated, need to be stored in a database with proper traceability behind the storage. This results in a huge amount of data stored in the database, locally or in the cloud. These data can be used to derive valuable insights by employing AI/ML algorithms and improving the internal processes’ efficiency and effectiveness. Since the data is very specific to that stakeholder of a supply chain in question, this will result in deriving insight with a narrow context. This might be useful in the short run. In the end, it is necessary to obtain critical data (as feedback) from various stakeholders of the supply chain to build a broad context. This puts blockchain into the foreground.

Each stakeholder needs to operate in dual-mode - one side is their existing IT infrastructure comprising numerous enterprise applications. On the other side is an external environment with suppliers, distributors, regulators, auditors, certifiers, and customers, as depicted in Figure 6. The two sides are connected through blockchain, which holds critical control data from various stakeholders.

Each stakeholder will be storing a huge amount of data in the database. However, selected critical control data is stored in the blockchain, accessible to other stakeholders of the supply chain [18]. The data layer will interact with the blockchain component to write data from the blockchain as a transaction, as illustrated in Figure 7. Each transaction would contain corresponding critical control data. The control data influence the performance and need to be identified in consultation with the other stakeholders [18]. Similarly, critical control data available in the blockchain can be read and stored in the local database. In short, various stakeholders of a supply chain will write critical control data to the blockchain and, if necessary, read critical control data from the blockchain resulting in the exchange of information as illustrated in Figure 7. This requires the implementation of suitable read and write services.

The blockchain contains transactions, and the information is stored as blocks, as illustrated in Figure 8. The setup consists of multiple authorized contributors and multiple verification nodes. Different nodes verify each transaction, and then a block is added to the previous blocks in the blockchain. The blocks
are encoded and cannot be manipulated; thus, making them secure. The databases behind storing the blocks are decentralized. The operations (or transactions) about preparing raw materials and semi-finished products are verified and stored as blockchain blocks by the suppliers. The information stored in the blocks is a sub-set of information created purely from the perspective of monitoring the processes by external entities.

Figure 6. Exchange of information among stakeholders of a supply chain employing blockchain [7, 14].

Now, regulators, auditors, certifiers, and others, who have access to the blockchain, can access the information stored in the blocks and confirm the operations. For example, certifiers can check if the operations are executed as described or see if there any deviations. Likewise, certifiers can check if a machine was calibrated or not as prescribed before commencing operations. Consequently, trust between partners is increased, transparency surrounding products is enhanced, and products are secured, and so on.

Suitable AI/ML algorithms can be applied to realize an intelligent supply chain, including the use of a CEP engine. Here, AI/ML algorithms will be implemented on data pertaining to a single stakeholder initially. This can assist in identifying new insights and can initiate suitable corrective actions. The identification of new insights can be considerably enhanced once the data is retrieved from the blockchain to create a broader context. In short, AI/ML algorithms will be implemented on data related to multiple stakeholders after blockchain implementation.
Each stakeholder of a supply chain has issues that need to be addressed. The identification of new insights either with the data from the single stakeholder or from multiple stakeholders is indispensable. The new insights need to be incorporated as services. This is crucial as services as issues encountered by the stakeholders’ change over a period of time.

4. Conclusions and Future Work
The article introduced the layered framework to realize smart manufacturing within a given stakeholder of a supply chain. It is crucial that various stakeholders exchange data or provide feedback to enhance the overall efficiency of the supply chain and fulfill the requirements of the customer in an efficient manner. Here, it is necessary to agree and define the critical control data that will be exchanged among the various stakeholders of a supply chain. Subsequently, this framework was enhanced to include blockchain for exchanging information among the various stakeholders of a supply chain. This data can be utilized to develop AI/ML models to address a selected situation and the models integrated into the layered framework as smart applications.
Figure 9. A possible use case of employing blockchain to exchange data in a supply chain.

An ideal scenario of the implementation of blockchain and intelligent supply chains is depicted in Figure 9. A blockchain has all the security mechanisms and consensus algorithms, but there are a few barriers to adoption. These barriers in the adoption of blockchain can be broadly classified under intra-organizational, inter-organizational, system-related, and external barriers [7]. For instance, blockchains are not easily scalable, require expensive hardware to run a node, and the synchronization of a new node into the network is slow as the node has to collect the entire copy of the blockchain ledger [31]. Furthermore, there is a lack of standardization in the industry, which means there is very limited interoperability [32]. Integration with legacy systems can be a problem as most of the blockchain protocols have been written in high-level languages and lack compatibility with the legacy system. The most important issues of all are the lack of awareness and the association of cryptocurrency with blockchain technology.

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