International Journal on Interactive Design and Manufacturing (IJIDeM) (2025) 19:681–694
https://doi.org/10.1007/s12008-024-01836-9

ORIGINAL ARTICLE

Smart manufacturing supply chain process strategy using intelligent computation techniques

R. Vijayapriya[1] · S. L. Arun[1] · K. Vengatesan[2] · Sayyad Samee[3]

Received: 20 October 2022 / Accepted: 26 March 2024 / Published online: 18 April 2024

Abstract

Advancement of intelligent and computational techniques like internet of things (IoT), machine learning (ML), artificial intelligence (AI), blockchain etc., gradually transforming the existing traditional manufacturing process to a smart process by developing a heterogeneous distributed environment. Considering the lack of transparency in the present manufacturing system with respect to information traceability of products, this paper discusses the IoT, ML and blockchain-based product traceability system. Two uses cases are considered in this study: market demand and buyers' priority-based manufacturing process. To start with the market demand-based manufacturing process, ML algorithms are framed to forecast the market demand of the product and to predict the supplier's profitability. Based on the prediction, the manufacturing process starts, and all the stakeholders (manufacturing organizations, shipping companies, dealers, and consumers) involved in the supply chain process engages in product information certification via blockchain. The paper also validates that with the implementation of blockchain, even the end user of the product knows the product manufacturing process and can effectively tracks the product information like quality of the material out of which the product is made, product delivery period, warranty, etc.

Keywords Blockchain · Manufacturing · IoT · ML · Supply Chain

1 Introduction

The demand for the production of intelligent, individualised and sustainable product leads to the evolution of new agile manufacturing process in the fourth industrial revolution Industry 4.0 [1]. The vision of Industry 4.0 is to empower devices with certain degree of interaction competence to communicate with other devices via intelligent control systems and internet [2]. Hence, with real-time application, large volume of manufacturing data is exchanged over the internet. Devices are trained to make local decisions autonomously, which influence the entire manufacturing operations [3]. One of the basic elements of manufacturing archetype is supply chain, and its transparency has become indispensable in the manufacturing process. Numerous products have been manufactured globally, however the product genuineness and flow like origin, development and shipment stages are not transparent. The product development crosses over vast network of manufactures, suppliers, logistics, warehouse, distributors, and stores that involved in production, goods supply, goods transportation, storage, delivery and sales. With the traditional supply chain process, the product journey at each stage remains unseen, subsequently fallouts to inadequacy in transparency. Nonetheless, customers wish to follow up every production stage to ensure the product authenticity. The transparent manufacturing supply chain ensures visibility of entire process to the stakeholders which aid in establishing trust in the system.

✉ S. L. Arun
arun.sl@vit.ac.in

R. Vijayapriya
vijayapriya.r@vit.ac.in

K. Vengatesan
vengicse2005@gmail.com

Sayyad Samee
samee.syd@gmail.com

1 School of Electrical Engineering, Vellore Institute of Technology, Vellore 632014, India

2 Department of Computer Engineering, Sanjivani College of Engineering, Maharashtra, India

3 Dept. of computer science, Al Sadara School, Al Ain, Abu Dhabi, UAE

Emerging technologies for instance edge, fog and cloud computing, internet of things (IoT), data analytics, machine learning (ML) and artificial intelligence (AI) paves a way for many opportunities in industrial sectors. These technologies offer numerous benefits like remote monitoring, enhanced productivity, safety, profitability, automation, cost and energy saving, quality, reliability, and flexibility. Application of these technologies with Industry 4.0 leads to smart manufacturing process including supply chain [4]. The main objective of smart manufacturing is to enhance the connectedness among the stakeholders such as manufacturers, warehouses, logistics, suppliers, distributors, and merchants. Also, enrich interconnection of other manufacturing supporting industries and form a valuable smart manufacturing network among entire manufacturing value chain [5].

Though smart manufacturing system intends to provide automation, remote control and monitoring, the manufacturing archetype lacks mechanism to govern security challenges. The manufacturing data may be tampered or attacked as per the present structural design of industrial control systems and the systems suffer from security issues. For instance, attackers may tamper with the performance information of aluminium and copper products in steel industry by modifying the strength and size data during product inspection. As these forging products can be employed in various fields ranging from defence to automobiles, these products may possibly create intense safety issues. Tampered and erroneous data impose significant threat in the interlinked manufacturing networks and fail to implement appropriate control mechanism and decisions making [6] and [7]. Traditional manufacturing system suffers from inadequacy of information monitoring and tracking, and robust control against system failures due to centralized structure.

To confront this security issue and to improve the system's efficiency blockchain technology can be implemented which is recently revolutionizing the business and industry sectors [7]. Being decentralized system, the technology offers transparency in each and every process flow employing the distributed ledgers [8]. Through inherited characteristics, the technology ensures trust via the transparency and traceability of any process in the corresponding network [9]. Presently blockchain is employed in manufacturing systems primarily to avoid fraudulent data injection/manipulation. The inherent and robust smart contract features of blockchain evade an intervention of third parties tampering with the data. The technology provides a new way of tracing the journey of a product, from production line till it reaches the end user. Implementation of blockchain technology with IoT radically changes the manufacturing supply chain.

Also, the activity of assets (operation management) which is the vital process of product manufacturing, supply, and service with IoT, big data analytics, cloud computational and blockchain implementation impact the economic and social factors in a positive way [10–14]. Operation management, manufacturing, and supply chain management which relies on centralized information technology systems to store and manage data are transforming to decentralisation, transparency, and visibility systems via the implementation of blockchain technology [15] and [16].

Several research works have been addressed to highlight the significance of blockchain in manufacturing. A secure smart contract based on Ethereum permissioned blockchain is proposed in [17] to obtain a complete framework to secure the cloud-based manufacturing operations. In [18] cloud manufacturing trust problem is addressed by implementing blockchain based trust system namely blocktrust. Initially, the cloud manufacturing framework is developed with capability pool, digital firm and certificate validating units. Then a peer-to-peer network is implemented using private blocktrust Hyperledger fabric. In [19] blockchain and fog computing-based security features is proposed for manufacturing equipment clusters. The developed system facilitates cloud manufacturing equipment authentication and privacy protection over the blockchain using Hyperledger fabric. To demonstrate the importance of trust management with the aid of blockchain implementation a unified framework for supply chain management headed for smart manufacturing process is implemented in [20–23]. The effectiveness of the proposed framework is presented considering coal mine machinery manufacturing scheme.

The existing manufacturing systems provide limited or zero option to optimally choose the needs of the members such as dealers, merchants, logistics providers, raw materials suppliers. Hence the product quality, quantity and economic benefits of these members will be nearly decided by the central manufacturing industry. In order to make the centralised control to decentralise this paper intends to frame two process flows with respect to the manufacturing process with the aid of blockchain. The remainder of this paper is organized as follows. The overview of smart manufacturing layers is detailed in Section 2. Section 3 describes two manufacturing processes: market demand based and buyer's priority-based process. The formation of ML algorithms to forecast the market demand strategy of the product and to predict the supplier's profit rate is discussed in Section 3. In continuation with the review of present market demand, Section 4 expresses the application of blockchain for secured smart manufacturing process. Finally, Section 5 draws the conclusions.

2 Smart manufacturing layers

New market demands and emerging technologies fascinate smart manufacturing process with the objective of attaining the evolutionary changeover from automation and control to remote monitoring and control. The different layer of smart manufacturing systems which encompasses the key technologies is depicted in Fig. 1 which includes physical, computational, application, business, and security layers.

2.1 Physical layer

At this layer, the physical entities range from manufacturers (including suppliers and logistic service providers) to dealers (including merchants, retailers) and customers who are interconnected among themselves through the products.

2.2 Computational layer

This layer details the key technologies of Industry 4.0 and smart manufacturing system for example IoT, big data, cloud computing, machine learning, blockchain and advanced analytical techniques.

2.2.1 IoT

Evolution of advanced technologies in the field of communication, computing devices, and wireless sensor networks makes the application of IoT in almost all the fields. Likewise, IoT-based supply chain is becoming vitally essential in the manufacturing process. Industrial IoT (IIoT) solution is developed with the aid of intelligent sensors, devices, actuators, and networking technologies. With IIoT all the equipment is connected, controlled, and monitored over the internet from anywhere by anyone/anything at any time. Since IoT integrates ubiquitous devices from various sites across the entire physical environment, to sense the real-time data, the system should have the provision to handle such a huge volume of data. Dealing large volume of information pertaining to IoT-based manufacturing is not only about the application of advanced computational algorithms to process the data in a parallel manner fairly it concerns environs which involves the selection of methods and modes of information conversion, storage, and information security infrastructure. Generally, IoT-enabled system rapidly gets millions of structured and unstructured data in various forms from a myriad of diversified resources. Hence, the obtained raw data need to be pre-processed for real-time integration, to perform streaming analytics and to optimize the production chain resources. Transferring all the data and initiating pre-processing in the cloud is cumbersome which increases the latency and requires higher bandwidth and implementation cost. The solution for this problem is to implement the basic computation nearer to the data sources i.e., edge computing.

Edge computing The edge computational layer converts the raw data generated by physical layer into useful information

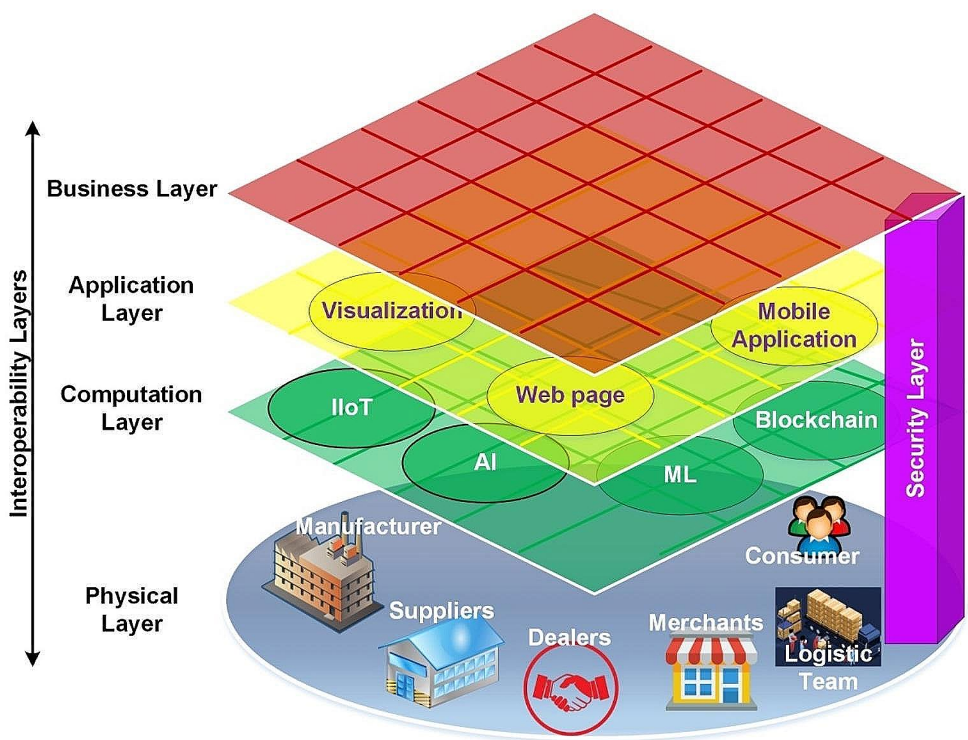

Fig. 1 Smart manufacturing layers

by incorporating pre-processing stages like data cleaning, filtering, transformation, and scaling to perform further analytics at the cloud. Computation techniques allow basic analytics and transform real-time big data locally i.e., as close as to its source. Hence, bandwidth, data rate and time are properly utilized by evading transferring all the data to the cloud. This results in reduced system latency, faster real-time responses, and enhanced system performance. Typically, local servers, industrial gateways, or the edge nodes distributed across the network are used to carry out pre-processing and these devices are comparatively powerful than the lower most physical layer devices. The edge computational techniques evaluate data and decide whether additional processing is required at higher layers; data need to be filtered, formatted, and decoded for additional processing; redirected to further destination. Overall this layer includes broad functionalities as follows: interoperability – enables real-time communication of data among various control devices provided by different vendors, integrates different forms of messages produced by industrial floor devices such as machine, measurement and process devices, supports integration of devices with different communication protocols; analytics-based events - activity comprises responses to numerous manufacture actions like accomplishing rule-based alerts/notifications and sending control signals back to the factory floor devices and equipment; pre-processing - includes data aggregation, filtering, and cleaning to refine the raw data; edge analytics – includes data analysis like product demand prediction in the market, raw materials requirements, prediction of suppliers profit etc.

Communication protocols Gateways provide the direct connectivity between the floor level device layer and the centralised cloud. Gateways are either hardware or software modules that performs protocols translation, additionally data encryption and decryption. Different communication protocols are used to transfer the data from physical to application layers. Link layer communication protocols such as WiFi, zigbee, bluetooth, are used to collect the data from the plant device nodes. Internet protocols such as IPv4 and IPv6 are used as a network layer protocols. The transport layer protocol may be a transmission control protocol (TCP/IP) or user datagram protocol (UDP) depending upon the application layer protocol. The application layer protocols include http with TCP/IP, constrained oriented application protocol (CoAP) with UDP, message queuing telemetry transport (MQTT) with TCP/IP and advanced message queuing protocol (AMPQ) with TCP/IP. They are used to interact with user or with the real-time application devices.

Cloud computing Cloud computing makes raw data useful by collecting, storing, and processing data from the physical and edge layers. Generally, IoT platform service providers handle these tasks in two different stages: data accumulation and abstraction. In data accumulation stage, an application programming interface is used to capture the real-time data and the data is stored and batch processed based on the request. This stage serves as a link between event-driven and query-driven data generation and consumption, respectively. The stage also determines the data relevancy in meeting the business requirements. Additionally, the stage provides the wide range of storage solutions, from data lakes (which stores unstructured data like images and video streams) to relational and non-relational databases. For example, to store big data, Microsoft Azure uses *Data Lakes* which act as a cloud based centralised repository and lets users to store structured and unstructured data at any scale. The overall objective is to sort the larger number of disparate data and to possibly store it in the most efficient manner. In data abstraction stage, data preparation is finalized to derive insights from the data based on the application. The process involved in this stage includes: integrating both IoT and non-IoT data from multiple sources; unification of different data formats; and accumulating data in one location or provisioning remote data monitoring/accessibility via data virtualization. Together, the data accumulation and abstraction stages cover hardware details and enhance smart devices interoperability. Cloud-based manufacturing, as a centralised one-shop, enables manufacturers to use advanced analytics on top of the data lake. Users may use a wide range of applications ranging from simple data visualisation to complicated streaming analytics, ML, and intelligent decision-making support. The data analytics in the cloud includes the visualization of data relationship between different participants in the form of blockchain, the timely update of the product location, etc.

2.3 ML and AI

Data availability in the cloud forms a dispersed data lake, which allows for industrial analytics to be performed on top of the stored data using AI and ML algorithms. The goal of industrial analytics is to discover hidden patterns in data and establish unseen correlations between them so that decision-makers may make better judgments. Advanced industrial analytics solutions can be deployed on-premises or in the cloud. Various cloud suppliers enable manufacturers to integrate and store big data, to employ cloud-based advanced analytics, and generate bespoke business solutions using cloud-based technologies. For example, GE's *Predix*, an industrial internet platform provides a marketplace to implement various apps and services like predictive and preventive maintenance, anomaly and outlier detection, and intelligent algorithms. Similarly, the Azure AI gallery provides a catalogue service for locating various ML algorithms for the IIoT. *AzureML*, a visual programming environment developed by Microsoft, has been incorporated to construct machine-learning algorithms. As a result, *AzureML* developers may share their algorithms with the community by creating an Azure AI gallery. Likewise, *MindSphere*, a cloud-based Industry 4.0 platform is introduced by Siemens which allows businesses to link their industrial machinery to the cloud and provides a marketplace for deployment-ready industrial apps.

2.4 Blockchain

Industry 4.0 and smart manufacturing foresee data access across various supply chain stakeholders such as logistics, customers, distributors, and suppliers. Information from numerous machines on factory floors is directed to the centralized network and product information may not be available to all users in the system. Blockchain technology might offer an alternative answer. It is dispersed and decentralised via peer-to-peer networks. Each network participant has the ability to access the data in the blockchain and the network stays synchronised. As an example, blockchain may be utilised for timely maintenance of industrial asset and for exchange of critical information across several enterprises. To reduce downtime in manufacturing production, repair and service providers might track the blockchain for maintenance and record their work on the blockchain for future use. Through blockchain, industrial plant equipment regulators would have access to asset records and can provide timely certification to assure the asset's safety for the workers. Blockchain also provision domain knowledge sources including linked open data, linked open rules, and linked open services. For an example, sensor-based linked open rules are a collection of interoperable rules used to analyse data supplied by sensors. A linked open service is designed to exchange and repurpose services and applications which may be used to build cross-domain Industry 4.0 applications. Considering manufacturing process, real-time data streams from different systems like logistics, weather and traffic may also brought into blockchain for real-time product location tracking. Further, at the data-analytic layer, these data may be coupled with other information, such as events affecting product shipments. This provides a fully transparent picture of the product flow and allows making decisions from the dispersed information centre in case of emergency or product gets lost.

2.4.1 Application layer

This layer uses software to evaluate data and deliver answers to crucial business concerns. Hundreds of IoT applications exist, varying in intricacy and purpose and utilizing several technology stacks and operating systems. Instances include device monitoring and actuation services, web and mobile applications for easy communications, business information services, and ML analytic solutions. Applications may already be created directly on top of IoT platforms which include infrastructure for software development as well as ready-to-use tools for data pre-processing, sophisticated analytics, and data visualization. Otherwise, IoT apps connect with middleware via application programming interfaces.

2.4.2 Security layer

As part of the digital revolution for company development and production reform, smart factories are being built at a rapid rate. However, cybersecurity threats are arising in systems, including operation and administration, because of their connectivity to networks and usage of open technologies. The expansion of smart factories necessitates the need to connect to external networks, use cloud services, and form supply chains, making security risks more important than ever. Large scale integration of devices and big data management result in concerns with information protection, privacy, and internet security. Furthermore, with the transition towards cloud-based distribution system and application of streaming analytics, traditional defect detection approaches are unsuitable for smart manufacturing. Most ML algorithms and open-source tools have concerns with scalability, simplicity of use, extensibility, and generalisation capabilities. The linked factory poses several cybersecurity issues. Fortunately, companies may employ well-established methodologies to alter the susceptible designs to more secure postures. Mapping connected devices across the workplace, segmenting the network to restrict invasions, monitoring traffic to identify threats inside these network segments, and codifying response, both organizationally and procedurally, is all steps forward.

2.4.3 Business layer

This layer draws the business model, overarching procedure, and rules that the system must adhere to. The business model layer protects the integrity of the streaming function values and establishes the regulatory and legal framework requirements. The business layer orchestrates the application layer's services and receives events that indicate the status of the business process.

3 Manufacturing supply chain process flow

Manufacturing process adds value to raw materials by transforming the materials to intelligent products. Upon the completion of manufacturing, the product is distributed to the consumers through a supply chain mechanism. Manufacturing supply chain involves numerous entities such as suppliers, merchants, dealers, consumers, logistics etc., as depicted in Fig. 2. With the conventional system (systems follows centralised architecture), it is hard to track the journey of the products due to the participation of different entities. Centralised structure stores the details of product journey in multiple databases which cannot be accessed by all the entities. Different entities will have access to different database but not to all databases. Additionally, the users/distributers/dealers who place the orders cannot track the product details when it is in the process of manufacturing. However, implementation of blockchain, in manufacturing supply chain enables product tracking at every stage and makes the system process smarter, transparent and secure. Based on the end consumer demand, the manufacturer will decide the unit of product production only if the requirement is in larger quantity.

This section details the architecture of manufacturing systems in two perspectives i.e., product development on its own based on the market demand (Market demand-based manufacturing) and product development based on the buyers' requirement (Buyers priority based manufacturing).

3.1 Buyers' priority-based manufacturing

Manufacturing supply chain is a unified set of business processes which encompasses activities starting from raw material procurement to delivery of final product to the customer. Delivery of right product to the right consumer at the right time and in the correct quantity is a major goal of an efficient and successful supply chain system. The product flow for buyers priority based manufacturing is depicted in Fig. 2 as indicated by dotted lines. The process flow is explained in six steps as follows:

3.1.1 Step 1: Order placement by the merchants to the manufacturer

Merchants place the product requirement details to the manufacturer which includes design, technology, specification and in some cases even the product prototype.

3.1.2 Step 2: Order received by the manufacturer

Following receipt of the merchant's order, the manufacturer examines the product specifications and contacts the suppliers to get the raw materials. The manufacturer provides suppliers with information such as the amount and kind of necessary materials.

3.1.3 Step 3: Order received by the suppliers

After the suppliers receive the data, the next step is to add an invoice along with the raw material specifications to keep the manufacturer up to date. The identified supplier obtains the order to deliver the raw materials after the manufacturer confirms the supplier's request. The supplier packs the order and adds details such as type, quantity and packaging date of the raw material. Upon the completion of order package, the supplier contacts the logistics teams to deliver the raw materials to the manufacturer.

3.1.4 Step 4: Logistic service

Before beginning the journey from the supplier's warehouse, the logistics service provider records the product type, dispatch time, driver name, vehicle number, and quantity of cartons. Products transportation through IoT-enabled vehicle allows suppliers, logistics teams, and manufacturers to receive real-time updates on the vehicle's location, the condition of the goods, the estimated date and time of product delivery.

3.1.5 Step 5: Raw materials received by the manufacturer

After receiving the materials, the manufacturer inspects them for quality and quantity. If the supplied materials are deemed to be in excellent condition and usable for manufacturing, the manufacturer initiates the supplier payment procedure right away. The payment would be automatically changed in the supplier's credentials. If the material is discovered to be in poor condition, a recall request will be made to the supplier. The manufacturer block is updated with all transaction data. The company begins production using the raw materials acquired. Integration of IoT into traditional manufacturing processes provides real-time tracking and monitoring of product completion status and quality. After the items are made, they are sent to the quality assurance (QA) team for quality control. The QA team inspects the product and updates the testing information. After receiving clearance from the QA team, the items will be sent to merchants. This is done with the assistance of a logistics service provider, and the team follows the approach outlined in Step 4.

3.1.6 Step 6: Order received by the merchant

After receiving the items, the merchant checks them and examines the QA test findings to confirm that the order received is proper and certified. If the items are verified to be correct, the payment procedure will be initiated.

3.2 Market demand based manufacturing

Market demand based manufacturing process flow is expressed in Fig. 2 as indicated by solid lines. The manufacturer themselves planned to develop the products based on the market demand. The demand strategy is predicted using machine learning algorithms as discussed in section IV. The market demand based manufacturing process flow is similar to the buyers' priority based manufacturing excluding step 1 in the previous sub-section. Stakeholders involved in this process flow are manufacture, raw materials suppliers, logistics, merchants 2 and consumers.

4 Computational algorithms

4.1 Machine learning

Movement of goods and information among and between commercial organizations, such as suppliers, manufacturers, and clients, is referred as a supply chain. The effective fulfilment of customer demand is the ultimate objective of supply chain management. AI techniques are crucial in the decision-making process since they allow the firm to do data analysis throughout the business process. Hence, the application of AI in various sectors in smart manufacturing process such as manufacturing industry, raw materials suppliers and logistic suppliers are briefly discussed in the following subsections:

4.1.1 Manufacturing industry

Demand forecasting is one of the essential features to estimate the future product/service requirements based on current and historical data as well as market factors. As every firm faces an unpredictable future, it is difficult to predict the future product demand. Thus, it is feasible to estimate future demand and produce items that will be in great demand in the near future by analyzing historical and current market data. As a result, the manufacturer can plan ahead of time and create the necessary items based on market demand. Aside from the products that the company need, this will help to identify potential purchasers for the company/production facility. Eventually, the proper projection may result in a profit for the firm. In other words, predicting demand is an essential component of successful management planning. Machine learning forecasts the future demands of businesses. For demand forecasting, raw sales data from the market are collected first, and then future sale/product demands are anticipated based on the data. This forecast is based on information gathered from many sources. The machine learning algorithm processes data from several modules to calculate weekly, monthly, and quarterly demand for goods/commodities. In demand forecasting, absolute precision is required; the more precise the system model, the more efficient it is. The most critical component of any bi-centric application or model is data. The following inputs were employed for the proposed model: technology/methodology, year-to-date sales data, sessional impacts, market fluctuations, competition, and user feedback. The steps involved in the ML based market demand prediction is shown in Fig. 3.

Consequentially, the raw materials planning effectively help in boosting inventory turnover, procurement quality, productivity, and customer satisfaction. As a result, the speedy and proper execution of the material demand plan will have a positive impact on the entire company's efforts. Based on the predicted demand, manufacturers can optimally plan the need of raw materials from supplier. The objective of the suggested optimization problem is minimization of raw materials purchasing cost and it subject to the follow constraints: maximum investment cost constraint; manufacturing constraint (product development); quality of raw materials constraints; delivery time constraint; transportation constraint. The steps involved the optimal raw materials planning problem is depicted in Fig. 3.

4.1.2 Raw material supplier

An AI algorithm to predict the supplier's profitability in delivering the requested raw materials of the manufacturer is given below:

Input: Manufacturer raw material demand.
Raw materials availability.
Market competition
Delivery time limit.
Transportation charges.
Customs clearance.
Output: Profit analysis for supplying raw materials.
Preparation of Data:
Collected input parameters over a period.
Select data for Training.
Select data for validation.
Select data for testing.
Choose a suitable classification-based machine learning algorithm.

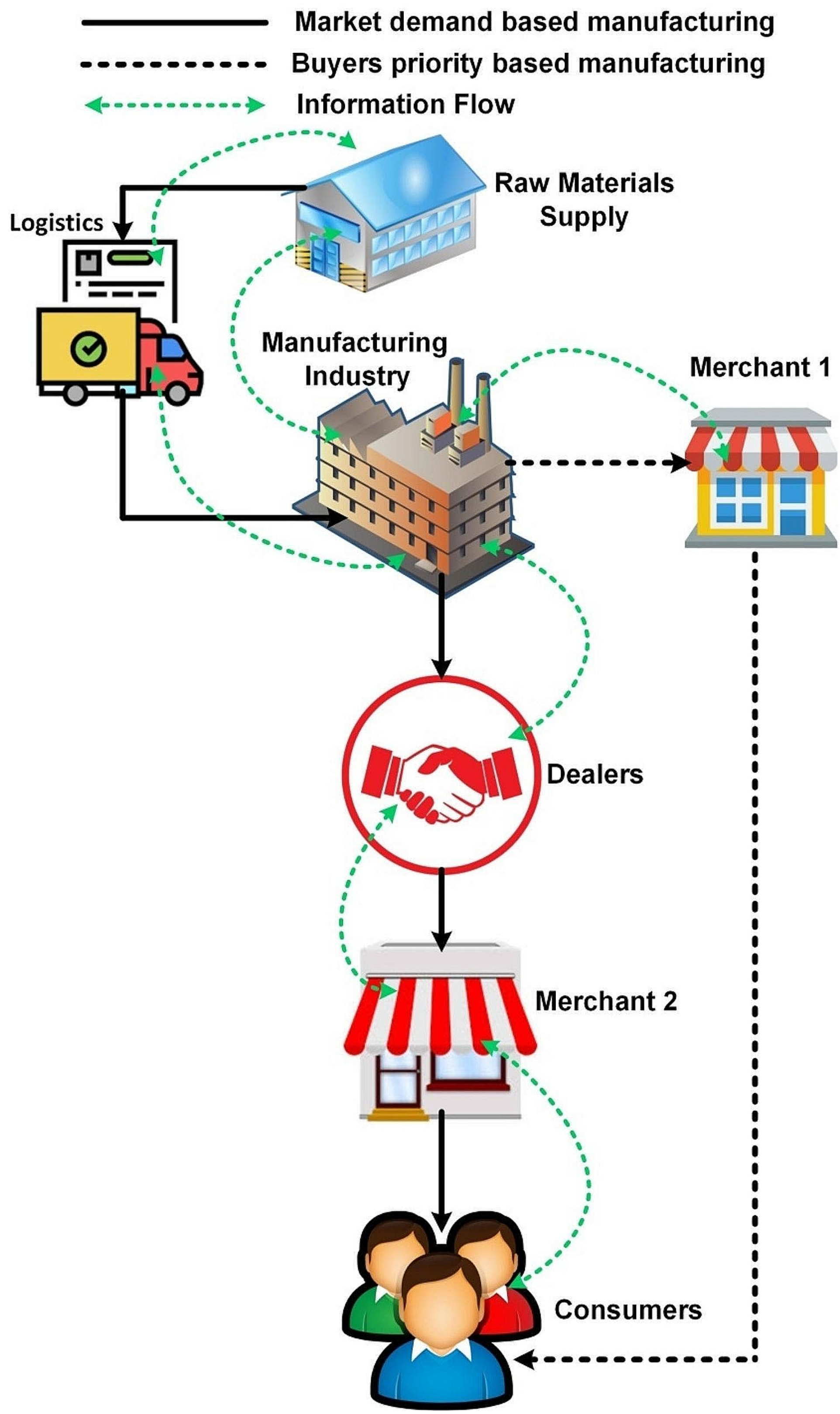

Fig. 2 Manufacturing supply chain process flow

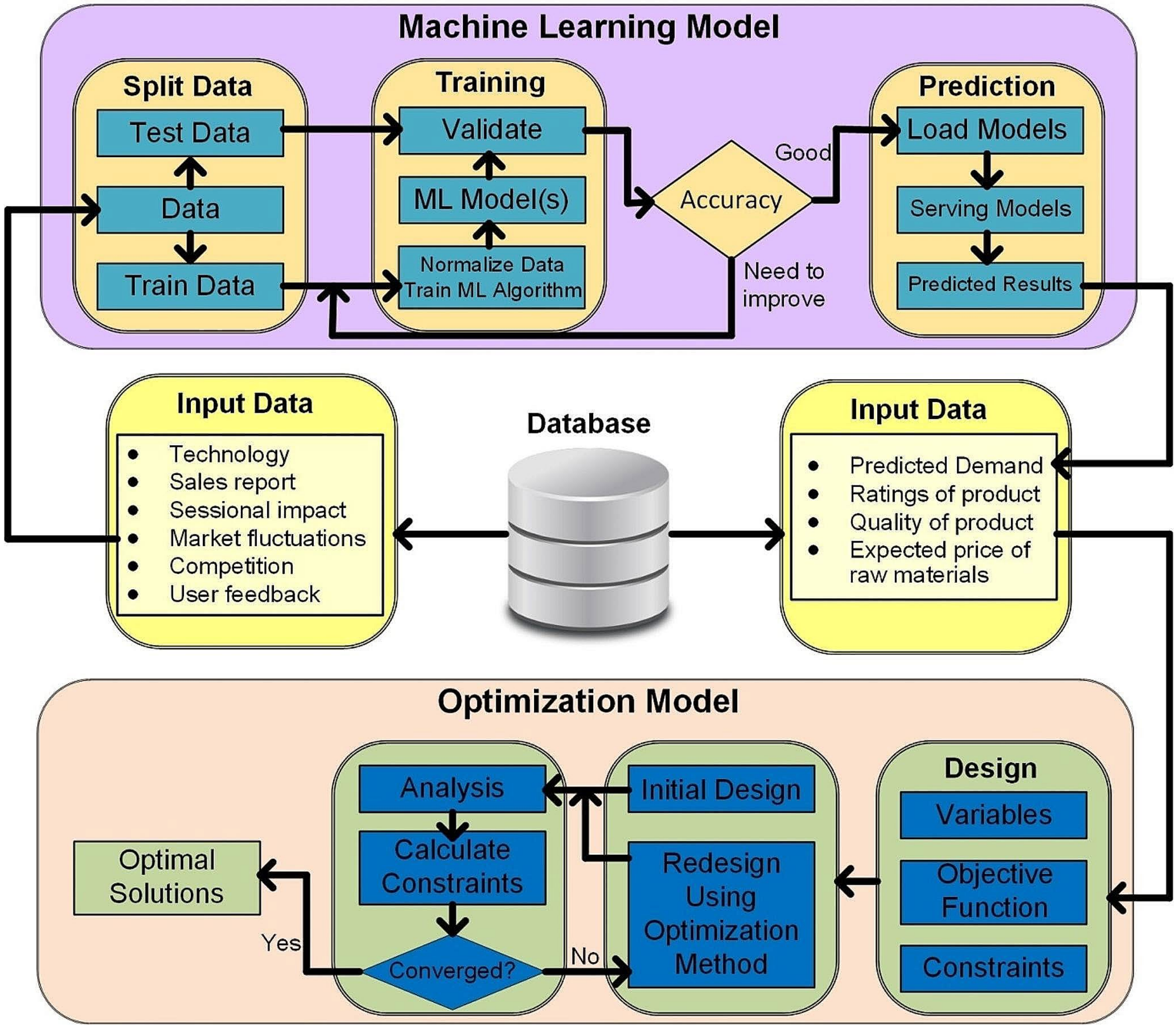

Fig. 3 AI based data analytics model

While (stopping criteria is not met) do.
Train the ML model for each learning data points.
Validate the ML model with testing data points.
end while.
Outcome: Profit/Non-profit.
* Stopping Criteria – User defined profit percentage which is evaluated based on the raw materials cost.

4.1.3 Blockchain

Supply chain is a promising area where blockchain technology can be applied to assure data privacy as well as transparency as per the stakeholder's requirements. The smart contract features of blockchain facilitate the assimilation of different stakeholders in the manufacturing supply chain process. Transparency and confidentiality can be improved by enabling the data integrity and audit trail via blockchain. For instance, blockchain can be employed to track the quality of diamond and thereby can reduce the bankers, guarantors, and customers risk of fraud. Hence, blockchain can be used to enable secure traceability of information certifications with respect to safety, quality, and reliability of the product. Complementary to digital twin, blockchain allows each physical entity to have a virtual entity i.e., a digital representation of physical entity. Supply chain is even made to be more agile through smart contracts mechanism where the stakeholders agree on contractual terms such as price, quantity, and quality. Hence, the stakeholders involved in the supply chain process can track the real-time status of every transaction by uploading the required terms into the blockchain. Contrary to the traditional approach, supplementary tasks that are deliberately significant for global e-commerce such as qualified supplier identification, price, negotiation and inventory monitoring are handled by smart contracts. Though the distributed network topology characteristics of blockchain make the information in the system to be transparent, the technology completely evades tampering with data. Blockchain consists of blocks connected in chain. Each block in the chain except the first block consists of three fields, previous block hash function, data and hash value of its own block, first block contains only its own hash function and the data. During the creation of the block, primary data pertaining to that block is stored and its own hash value is created. Over the period of time, the block records all activities involved in the block and for every activity change in the block, its own hash value is updated and each transaction is marked with time stamp. Hence, to maintain the link between the blocks, proof of concept (PoC) need to be carried out to update the previous hash value of the consecutive blocks. Encryption, chained data structure, time stamped function, smart contract, and consensus mechanism are the key technologies of blockchain. Consensus mechanism is the procedure of making agreements among the nodes involved in the network. Normally, PoC is used as consensus mechanism to validate the originality of the transaction that happens in a particular block. The following are the rules for nodes to get accounting rights: (1) The node initially packs all the data and computes the transaction data's root hash. (2) The node obtains a random integer that fulfils the PoC formula. When a hash value matches, it is recorded in the block and disseminated throughout the network. The hash value acquired by performing the hash function for each node in a single time under the PoC process are uniformly divided between 0 and $2^{256} - 1$. The SHA-256 algorithm has a spatial dimension of 2^{256}. For 'n' participating nodes in the network, and if each entity's computing power is equal, the probability of a node finding the current block's bookkeeping rights is the ratio of the probability of obtaining the first block hash value to the sum of the probability of obtaining the entire block's hash value.

The blockchain technology archives all transactional information that happens and provides effective and clear process flow, higher data security. Blockchain technology application in the field of supply chain management for product traceability and security play a significant role to uphold the market order and to improve the product consumption rate. Blockchain stores manufacturing, logistic, and transactional information of the products. The technology not only preserves the information but also makes it impossible to tamper with and substantially resolves information traceability and anti-tampering problems. Nevertheless, more IIoT technologies must be introduced to confirm the information posted to the blockchain is accurate, useful, and complete. In current product information traceability practice, IoT technology is typically merged, and information is accurately and neutrally supplied to the product information blockchain via access to the IoT information gathering terminal.

4.1.4 Architecture

Advancement of wireless sensor technology and reduced sensor cost make IoT technology a key way of intelligently managing the industrial operations. The architecture of manufacturing supply chain system based on IoT and blockchain technology for product information tracking framework is illustrated in Fig. 4. The IoT based product tracking system has a dispersed managing approach, and uses technologies like wireless sensor networks, communication protocols, embedded systems, etc., to collect and send data from product supply chain system to the cloud. Every distribution node in the manufacturing supply chain system is utilized as a data gathering point and the product tracking framework collects the data from the sensor nodes using the gateways. The collected product's information of each node in the network is stored in the blockchain. In this work, product manufacturers, raw material suppliers, logistics, dealers and consumers are considered as nodes in the blockchain network. The product tracking blockchain network contains products digital entries like basic data, product association information and certification. The blockchain based product quality traceability system describes the patterns of information interaction and exchange among each and every node in the network. Any stakeholders involved in the manufacturing supply chain process can register in the blockchain system using legitimate identification proof, and the system can create private and public keys at random for each user. When the user interacts with the system, the private key is used to encrypt and decode the exclusive data, and the public key is used to verify the user's identity. In this system, the user can add and update each product data according to the system's agreed-upon authorization, and the system will send the information on to the downstream user. The technology requires that the user encrypt the product information using the private key and put it into the blockchain only when they are at a specified link position. Furthermore, to maintain the transparency of product data, when items are circulated on the blockchain, the system assures the legality and fairness of the transaction process using smart contracts. Users in the manufacturing supply chains may now access crucial information, and regulators will be tracking the product-related data.

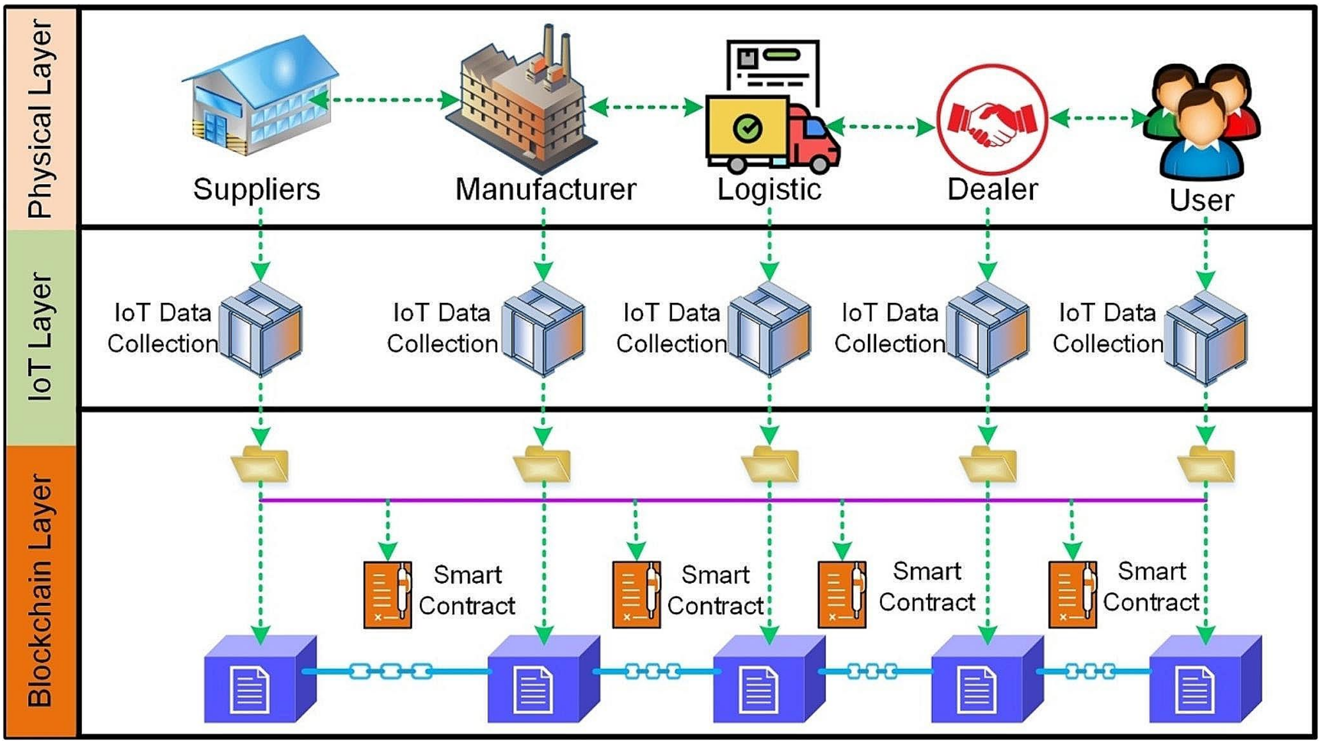

Fig. 4 Smart manufacturing architecture with IoT and blockchain

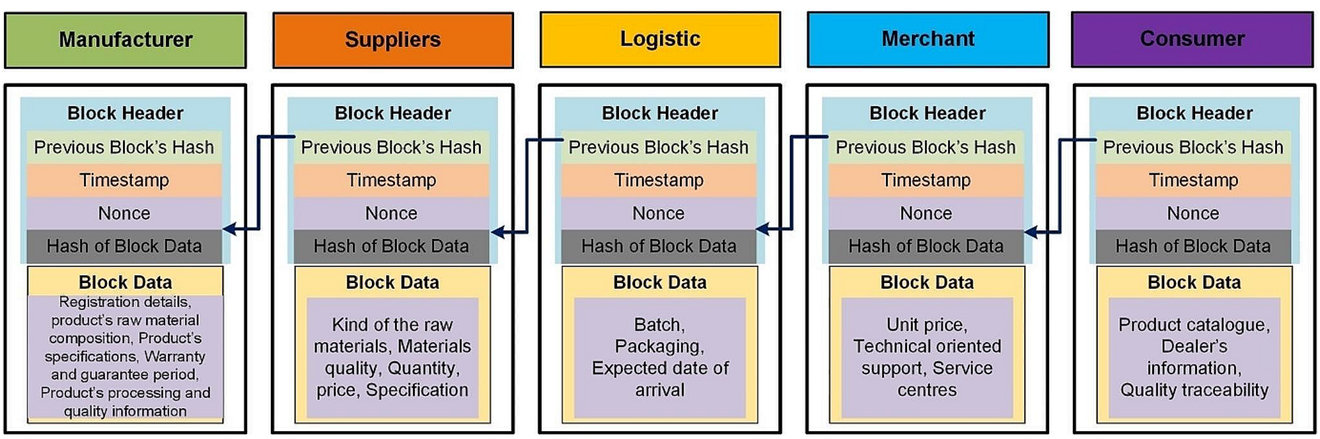

Fig. 5 Data Relationship Blockchain Network for Smart Manufacturing Process

4.1.5 Data relationship network

The block's information of different nodes involved in the blockchain network is elaborated in this section as shown in Fig. 5. The block data of the product manufacturer includes the enterprise's registration details, product's raw material composition, product's specifications, warranty and guarantee period, product's processing and quality information. Supplier's block contains the kind of the raw materials, materials quality, quantity, price, specification. Details such as unit price, technical oriented support, service centres, etc. are included in the merchant's block. The logistic block contains information like batch, packaging, expected date of arrival, etc. The product user's information block contains product catalogue, dealer's information, quality traceability, etc. Using the blocks information, the product supply and its associated dispute resolution efficiency can be improved by tracing back or up the impact in case of any issue raised at a node.

4.1.6 Product traceability design

Traceability and tracking are the two important features need to be addressed in the supply chain process. When

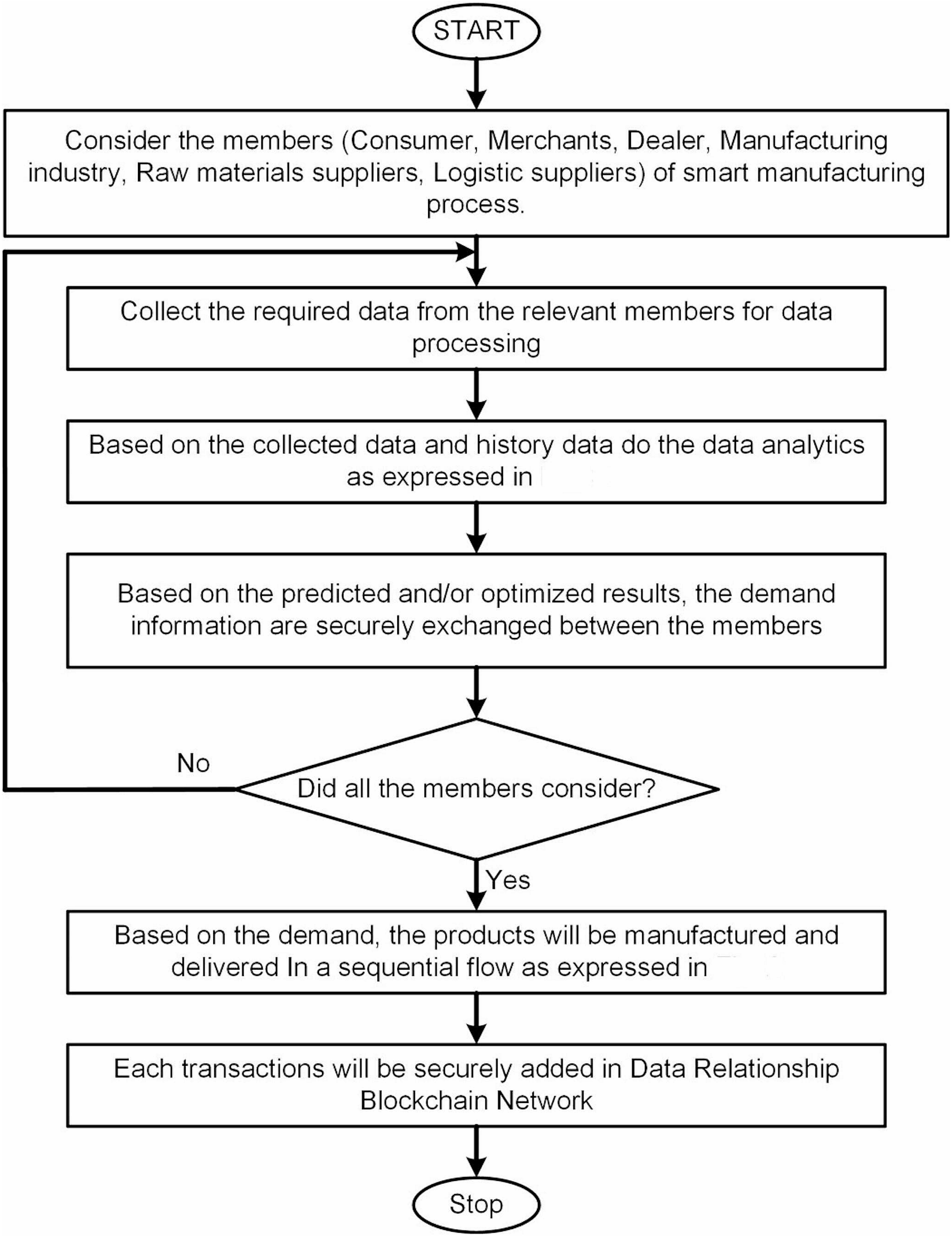

Fig. 6 Flowchart of proposed methodology

there are quality issues in the supply chain, traceability implies that items can be traced and processed from downstream to upstream along the manufacturing supply chain nodes in the network. The capacity to trace the course of items along the network and recollecting them in a timely way in case of any problem with the supply chain is referred to as tracking. The following is the procedure for tracking the issue with each link:

Manufacturing Link Companies enter raw material ingredients, raw material suppliers, product manufacturing process data, product quality data, and associated responsible personnel into the system. When trading happens, notify downstream members of the trade with the item identification code, product identification code, and logistics unit information.

Flow link Upstream information such as trade item identification numbers, product name and variation, number of logistical units, and shipper identification code is collected by distribution suppliers, distributors, and retailers. Output batch number, consignee identification code, date of receipt, downstream delivery, package temperature and humidity, as well as product transit can be tracked.

Product usage link The customer can scan the QR code or electronic product code to acquire not only the product circulation path between the producer and the merchant, but also product circulation node information and product information, as well as record product usage.

As a result, the system employs IoT and blockchain technology to monitor the production, processing, product flow and usage, as well as to identify the source of raw materials, product destination, and investigate the cause of safety accidents caused by product material problems. The overall methodology of the proposed smart manufacturing process is depicted as a flowchart in Fig. 6.

5 Conclusion

The development and execution of secure product traceability is a crucial approach for resolving quality and safety issues with any product, from raw material supply to product manufacturing and usage. In manufacturing process, it is essential to safeguard the product quality and safety, to promote the product brand building, and to deal with emergency safety mishaps. In this paper, the product traceability is examined utilizing blockchain-based IIoT. Manufacturing companies, suppliers, logistics, dealers and consumers may all engage in product information certification through the system. Consumers can successfully avoid the problem of partial information and poor transparency in the traditional information traceability procedure. Also, consumers can efficiently trace the product quality and effectively participate in service and maintenance oriented call via blockchain. Overall the system provides an excellent execution strategy to support the manufacturing sector transformation and upgrading.

The proposed methodology considers only one manufacturing industry which supplies the end consumer demands. However, the real time applications consider the competition among different manufacturing industries. Considering this scenario other members like deal, merchants and end consumers can opt for the reliable service from the manufacturing industries with the intention of minimal cost and better quality. In order to implement this solution a secured open supply chain market can be proposed as a future work.

References

1. Moghaddam, M., Cadavid, M.N., Kenley, C.R., Deshmukh, A.V.: Reference architectures for smart manufacturing: A critical review, J. Manuf. Syst., vol. 49, pp. 215–225, Oct. (2018)
2. Panetto, H., Iung, B., Ivanov, D., Weichhart, G., Wang, X.: Challenges for the cyber-physical manufacturing enterprises of the future, Annu. Rev. Control, vol. 47, pp. 200–213, Feb. (2019)
3. Kobzan, T., Biendarra, A., Schriegel, S., Herbst, T., Müeller, T., Jasperneite, J.: Utilizing blockchain technology in industrial manufacturing with the help of network simulation, in Proc. 16th Int. Conf. Ind. Informat., Porto, Portugal, Jul. pp. 152–159. (2018)
4. Lasi, H., Fettke, P., Kemper, H.G., Feld, T.: Hoffmann. Industry 4.0. Bus. Inform. Syst. Eng. **6**(4), 239–242 (2014)
5. Lu, Y.: Industry 4.0: A survey on technologies, applications and open research issues. J. Industrial Inform. Integr. **6**, 1–10 (2017)
6. Sitharthan, R., Vimal, S., Verma, A., Karthikeyan, M., Dhanabalan, S.S., Prabaharan, N., Rajesh, M., Eswaran, T.: Smart microgrid with the internet of things for adequate energy management and analysis. Comput. Electr. Eng. **106**, 108556 (2023)
7. Loganathan, A.S., Ramachandran, V., Perumal, A.S., Dhanasekaran, S., Lakshmaiya, N., Paramasivam, P.: Framework of Transactive Energy Market Strategies for Lucrative Peer-to-Peer Energy Transactions. Energies. **16**, 6 (2023). https://doi.org/10.3390/en16010006
8. Ahram, T., Sargolzaei, A., Sargolzaei, S., Daniels, J., Amaba, B.: Blockchain technology innovations, in Proc. IEEE Technol. Eng. Manag. Conf., Santa Clara, CA, USA, Jun. pp. 1–6. (2017)
9. Yuan, Y., Wang, F.: Blockchain and cryptocurrencies: Model, techniques, and applications, IEEE Trans. Syst., Man, Cybern., Syst., vol. 48, no. 9, pp. 1421–1428, Sep. (2018)
10. Abeyratne, S.A., Monfared, R.P.: Blockchain ready manufacturing supply chain using distributed ledger. Int. J. Res. Eng. Technol. **5**(9), 1–10 (2016)
11. Slack, N., Chambers, S., Johnston, R.: Operations Management. Financial Times Prentice Hall (2010)
12. Hofmann, E., Rüsch, M.: Industry 4.0 and the current status as well as future prospects on logistics. Comput. Ind. **89**, 23–34 (2017)

13. Li, Z., Barenji, A.V., Huang, G.Q.: Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform. Rob. Comput. Integr. Manuf. **54**(May), 133–144 (2018)
14. Ferdows, K.: Keeping up with growing complexity of managing global operations. Int. J. Oper. Prod. Manage. **38**(2), 390–402 (2018)
15. Rossit, D.A., Tohm´e, F., Frutos, M.: Industry 4.0: Smart Scheduling. Int. J. Prod. Res. **57**(12), 3802–3813 (2019)
16. Tapscott, D., Tapscott, A.: How blockchain will change organizations. What Digit. Future Holds. **58**(2), 10–13 (2018)
17. Wang, Y., Han, J.H., Beynon-Davies, P.: Understanding blockchain technology for future supply chains: A systematic literature review and research agenda. Supply Chain Management: Int. J. **24**(1), 62–84 (2019)
18. Arun, S.L., Bingi, K., Vijaya Priya, R., Jacob Raglend, I., Hanumantha Rao, B.: Novel Architecture for Transactive Energy Management Systems with Various Market Clearing Strategies, Mathematical Problems in Engineering, vol. Article ID 3979662, 15 pages, 2023. (2023). https://doi.org/10.1155/2023/3979662
19. Ajay, K., Abhishek, K., Pranav, N., Rukunuddin Ghalib, M., Cheng, A.S.X.: Secure Smart Contracts for cloud-based Manufacturing Using Ethereum Blockchain. Wiley (October 2020)
20. Barenji, R.V.: A blockchain technology based trust system for cloud manufacturing. J. Intell. Manuf. **33**, 1451–1465 (2022)
21. Tharaka Hewa, A., Braeken, M.: October Liyanage and Mika Ylianttila Fog Computing and Blockchain-Based Security Service Architecture for 5G Industrial IoT-Enabled Cloud Manufacturing. IEEE Trans. Industr. Inf., **18**(10), (2022)
22. Yue Wuac YingfengZhang: An integrated framework for blockchain-enabled supply chain trust management towards smart manufacturing. Adv. Eng. Inform., **51**, 101522, (2022)
23. Sitharthan, R., Madurakavi, K., Jacob Raglend, I., Palanisamy, K., Belwin Edward, J., Rajesh, M., Dhanabalan, S.S.: Performance Enhancement of an Economically Operated DC Microgrid With a Neural Network–Based Tri-Port Converter for Rural Electrification. Frontiers in Energy Research, 10, p.943257. (2022)