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An Overview: Applying Blockchain Technology to Improve Traceability in Manufacturing

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Abstract

Global production and distribution speed bring a renewed focus on the safety, quality and validation of several important criteria in supply value chain. There are a growing number of issues related to safety and contamination risks that have established an immense need for effective traceability systems that act as an essential quality management tool ensuring adequate safety of manufacturing products. Traditional systems face challenges like centralized management, unclear information, and unsatisfactory data reliability. Basic IoT traceability systems offer some solutions but often rely on centralized models, making real-time tracking difficult. Thus, there is a call for a strong end-to-end track and trace system in manufacturing to improve product safety and reduce defects. The research proposes a Traceable Resource Unit (TRU) system using blockchain technology to enhance transparency and credibility. Blockchain can improve traceability by providing security and a clear transaction history, although its full advantages and development methods are still being explored.

Keywords
Blockchain, systematic literature review, manufacturing

1. Introduction
Industries are using advanced technologies, like cloud computing, IoT, and blockchain, to increase automation and productivity while lowering costs and improving reliability (Mohamed and Al-Jaroodi 2019). Product recalls harm sales and reputations, making early problem resolution crucial (Bortoli and Freundt 2017). The 2017 listeriosis outbreak in South Africa resulted in 193 deaths (Thomas, Govender and McCarthy 2020) , and the US has over 48 million annual cases linked to product failures facilities (Stephenson, Coleman and Azzolina 2024). Effective tracking and traceability are essential for managing recalls and identifying supply chain issues, with blockchain offering secure record-keeping to enhance trust and security (Raut, et al. 2020). The research reviews literature on blockchain technology and traceability resource units in a manufacturing environment. The research summarized literature from different authors of design science research as follows (Peffers, Tuunanen and Niehaves 2018, Thuan, Drechsler and Antunes 2019) and assumed the approach of conducting the research from the point of view of an involved person, driven by an interest in the field of study and the aims to create knowledge to solve problems.

The research evaluates articles discussing how blockchain can solve manufacturing challenges of security, and reliability in smart manufacturing. Finally, the research highlights the traceability features of blockchain, like non-tampering and smart contracts, to enhance supply chain value exchange.

1.1. Objectives

The research aims to investigate traceability systems in the glass manufacturing industry using design science research. It seeks to provide valuable knowledge and tools for organizations through theory, artifact, and practice (Weigand and Johannesson 2023). Authors discuss the importance of defining the artifact clearly (Venable 2010) and identify relevant elements for different types of artifacts. Design science research focuses on creating practical solutions, particularly in information technology (Ceusters and Smith 2015). The purpose of the research is to explore the significance of blockchain technology today, focusing on its application in manufacturing. The research aims to identify and examine how blockchain technology can improve production traceability in manufacturing. It will systematically explore the benefits of using traceable resource units and blockchain in the industry. The investigative questions probe the application of blockchain technology in the manufacturing industry's supply chain based on the literature reviewed by scholars who have investigated the technology of blockchain.

RQ1: Can blockchain technology provide traceability and reliability of the supply chain?
RQ2: Can blockchain technology improve trust in the manufacturing line?
RQ3: How can transparency of the manufactured goods be achieved using blockchain technology?

The theory is the main goal of the research to explore blockchain technology applications. The objective arises from the research questions about how blockchain can be used in manufacturing and its benefits. The research design uses a methodology study to connect theory and practice, assessing results from the theory through a research case study. Evaluating DSR can be challenging due to its complex nature. Evaluation is crucial to determine if an artifact functions well. Authors proposed discrete testable hypotheses for evaluating design theories' processes and products (Herselman and Botha 2015). Therefore, the blockchain is defined as the research artifact and traceability becomes the sub-artifact of blockchain. Design science research methodology is important for conducting research in disciplines oriented to creating an artifact that serves as solutions to a defined problem. With the understanding that design science research is a problem-solving paradigm that seeks to enhance human knowledge (Vom Brocke, Hevner and Maedche 2020).

2. Traceability

Traceability is an ability to track and trace the history of a product, process and data throughout the lifecycle by means of record documentation, verification of information in terms of production data, quality control, compliance, safety, and efficiency (Garcia-Torres, et al. 2019). Traceability allows for the following of a product and its components throughout the different stages of the supply chain, linking the product attributes (Angelo , et al. 2020). Originating from the food and agriculture sector in the 13th century to prevent disease (Çağla 2021), traceability was defined in ISO 8402 of 1994 (Csavina, et al. 2017) and later was replaced by ISO 9000 in 2000, which redefined it (Rogala and Wawak 2021). Many of the definitions of traceability are related to the food industry standards and regulations considering the entire product lifecycle by means of product records identification (Olsen and Borit 2018). Traceability is a critical risk management tool used by organizations to focus on compliance and quality (Schuitemaker and Xu 2020).

2.1. Benefits of traceability

Traceability provides organizational benefits in product lifecycle management in using data collection, tracking and tracing and processing information therefore reducing the response time in locating related information and reworking the products (Angelo , et al. 2020). Scholars agree that traceability reduces cost (Xu, Zhao and Liu 2020), impact production quality control (Zhou and Xiaorong 2017), operational efficiency, and regulatory compliance (Angelo , et al. 2020). Traceability has become a critical tool in organizations in the interpretation of data and improving production safety (Olsen and Borit 2018). Literature advocates the use of traceability features on production processes that are complex to cope with ambiguities and challenging obstacles (Wowak, Craighead and Ketchen 2016).

2.2. Traceability in manufacturing

Organizations that lack the ability to trace their supply value chain run the risk of infringing on ethical production practices, abiding by legislative compliance and production safety (Hastig and Sodhi 2020). Organization apply monitoring systems to gain understanding and knowledge of their production facilities from inbound logistics, raw materials, processing, quality assurance, parts applications, packaging and outbound logistics (Abeyratne and Monfared 2016). Product lifecycle management requires manufacturing organizations to have the ability to monitor and investigate areas of their manufacturing processes to provide transparency, visibility and traceability (Sodhi and Tang 2019). For manufacturing organizations, traceability is important for tracking the origins of manufacturing parts, inventory, and delivery of inbound materials and outbound finished products. It helps manufacturers to understand complex assembles of their products and monitor production information in the value chain. Manufacturing traceability covers the entire product lifecycle, including raw materials, components, machines, quality data, and operators (Shou, et al. 2021).

3. History of blockchain

Like most systems, the evolution of blockchain is traceable through the different time periods. Figure 1 below illustrates the evolution of blockchain adapted from the description of different sources. In 1991, authors Stuart Haber and Scott Stornetta pioneered cryptographic techniques for timestamping digital documents (Singh 2022). In 2008, Satoshi Nakamoto introduced blockchain for secure transactions, promoting trust and security (Satoshi 2008). In 2010, Bitcoin was launched to be purchased, allowing users to exchange Bitcoin, which value grew significantly, reaching over $1000 by the end of 2013 (Luther 2019).

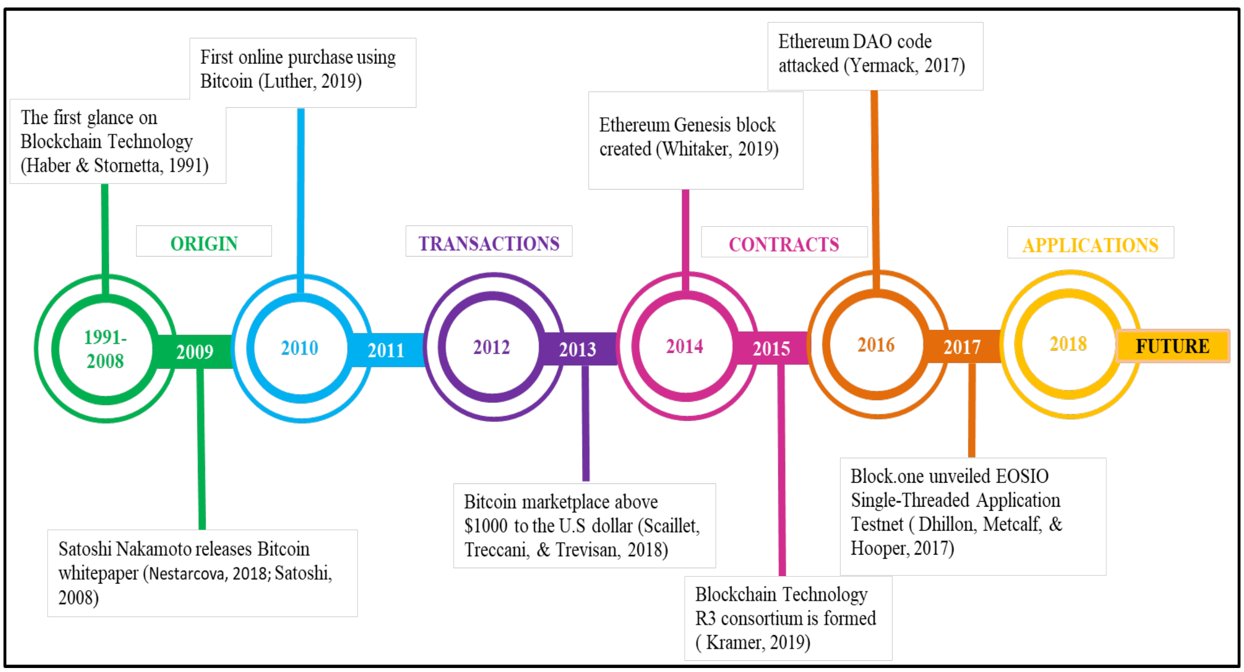


Figure 1. Blockchain technology historical progression

References of Figure 1: (Kramer 2019, Whitaker 2019, Luther 2019, Scaillet, Treccani and Trevisan 2018, Yermack 2017, Dhillon, Metcalf and Hooper 2017, Satoshi 2008, Haber and Stornetta 1991, Nestarcova 2018)

In 2014, Vitalik Buterin created Ethereum which allowed its users to use Bitcoins easier (Whitaker 2019). In 2015, the R3 Consortium was formed to address blockchain issues by developing a Hyperledger Fabric. A 2016 hacking incident revealed Ethereum's security flaws (Yermack 2017). In 2017, Block One launched EOSIO for decentralized block production. Research outlines how cryptocurrencies use cryptography for secure data handling, covering confidentiality, integrity, non-repudiation, and authentication, commonly used in banking, passwords, and e-commerce, employing three cryptography techniques (Swathi, Vivek and Rani 2016). The symmetric-key method involves a shared key between sender and receiver. The sender encrypts text with this key, and the receiver uses it to decrypt the message (Yaga, et al. 2018). This system provides secure information for civilian use at a lower cost than military methods. Public-key cryptography uses two keys: a public key for encoding and a private key for decoding (Wu, Guo and Susilo 2019). Blockchain cryptographic hashes protect the distributed ledger by connecting previous blocks. Any change requires 51% control which will recalculate the hashes. Adding a block locks the data on the chain which makes changes impossible without compromising the chain integrity (Tredinnick 2019). Linking hashes ensure blockchain integrity without a trusted third party.

3.1. Blockchain in manufacturing

The manufacturing process involves turning raw materials into finished goods in a value chain which involves design, sourcing materials, assembly, and distribution (Nguyen, et al. 2020). The process utilizes the use of machinery, engineering, human operations and techniques to efficiently create a product (Zhu, et al. 2022). In such cases as shown in Figure 2, the raw material is transformed into components through machining and molding, component assembly into final products and rigorous quality controls and inspections and finally into packaging and distribution. There are four departments that form every manufacturing process which are engineering research, design and development. Secondly, production operations, planning and control, maintenance, packaging, and supply chain logistics. The third aspect is information technology, financial control, human relations and administration. Lastly, the marketing and sales of the manufactured products (Fawcett and Magnan 2002, Rejeb, et al. 2021). The goal is to use unearth opportunities for organizations to use automation and data analysis to improve their production efficiencies (Phuyal, Bista and Bista 2020). This can be achieved by monitoring systems and traceability components into the process to formulate a quick, detailed and accurate analysis of the manufacturing process (Wang, et al. 2022). Blockchain technology is set as one of the technologies that drive the manufacturing process in the smart manufacturing industry (Kamble, Gunasekaran and Gawankar 2018). Blockchain technology has the ability to increase the transparency and trust between the different stages (Tredinnick 2019) of the manufacturing process from raw material to the delivery of the final product to reduce the bottlenecks in the process.

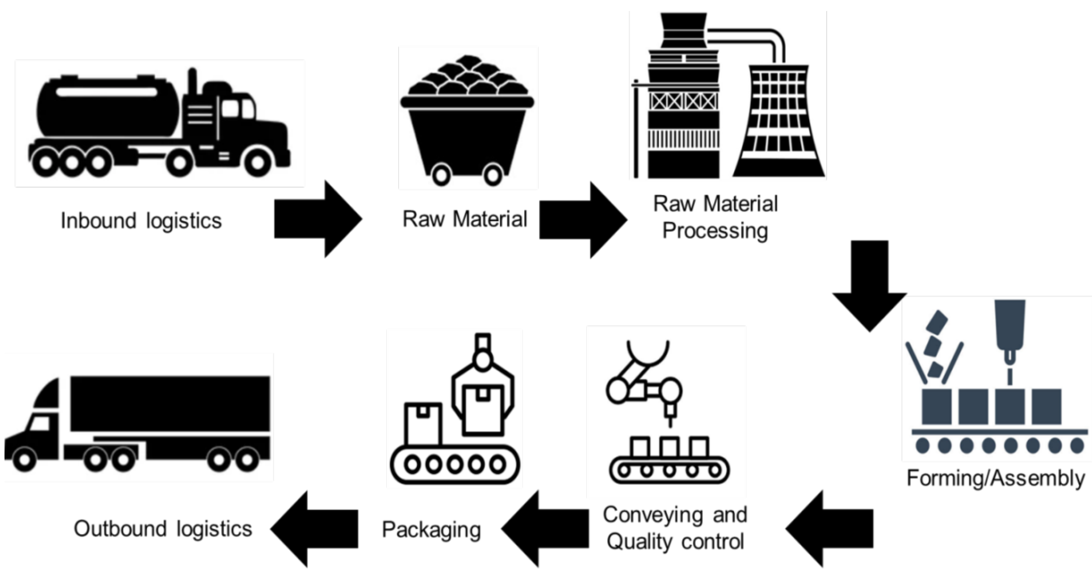


Figure 2. Typical glass manufacturing process

The IoT linked system as demonstrated on Figure 3, shows that blockchain can be used to record the process variables like temperature, moisture, location and the environment around the quality of the final product. Any deviation on the conditions of the product triggers an alert to the manufacturer to take the appropriate action (Tschorsch and Scheuermann 2016, Yuan and Wang 2016). The uses of blockchain technology and IoT presents a broader solution into manufacturing by ensuring that the manufacturer takes the market advantage in terms of transparency, competitiveness and product integrity (Lei, et al. 2017, Kapitonov, et al. 2018). For blockchain contracts to be executed, the pre-programmed agreements and conditions need to be implemented and met (Alharby and van Moorsel 2018) in this case the manufacturing recipes need to be inputted at the beginning stages of the process. Smart contracts in blockchain have internal clauses embedded into the systems using software's like Python or Solidity to be able to execute blockchain functions (Bahga and Madisetti 2016).

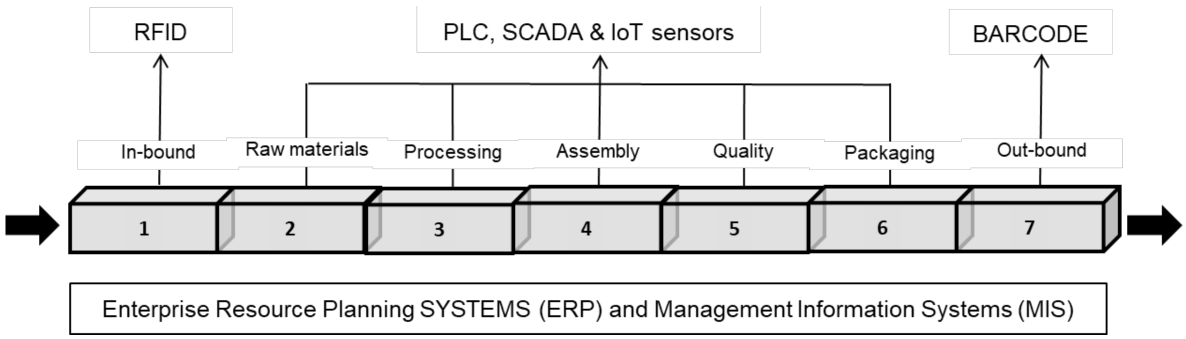


Figure 3. Link between technology and the glass manufacturing process

The smart contracts have an internal unique address that is triggered whenever a transaction is pinged to that specific address to execute a command autonomously that can alter the distributed ledger and make a record of the change (Weber, et al. 2016). Manufacturers can utilize blockchain to reallocate their resources in order to mitigate process risks and be able to track and trace the changes in the process line therefore increasing transparency in the organization (Risius and Spohrer 2017). As stated earlier, to change all nodes the system needs 51% percent therefore an agreement in the manufacturing value chain needs to be reached for a process change. This enhances transparency in the system giving the manufacturer's ability to make timeous decisions to ensure that the system has the sustainability (Zheng, et al. 2020).

4. Case study

The research utilizes a glass manufacturing facility to investigate the traceability aspect of applying blockchain technology. Traceability is one of the characteristics of blockchain technology (Guégan and Henot 2019). . Figure 4 illustrates the process flow of a glass manufacturing facility where raw materials such as silica sand, soda ash, dolomite, limestone, sodium sulphate, and cullet are received into silos and bunkers (Khan, Ahmad and Butt 2023). The recipe is formed and melted through a molten glass furnace with automatic control and monitoring (Zhou, Zhao and Chen 2019). The molten glass is put under high pressure to form different glass containers, annealed, inspected and packaged.

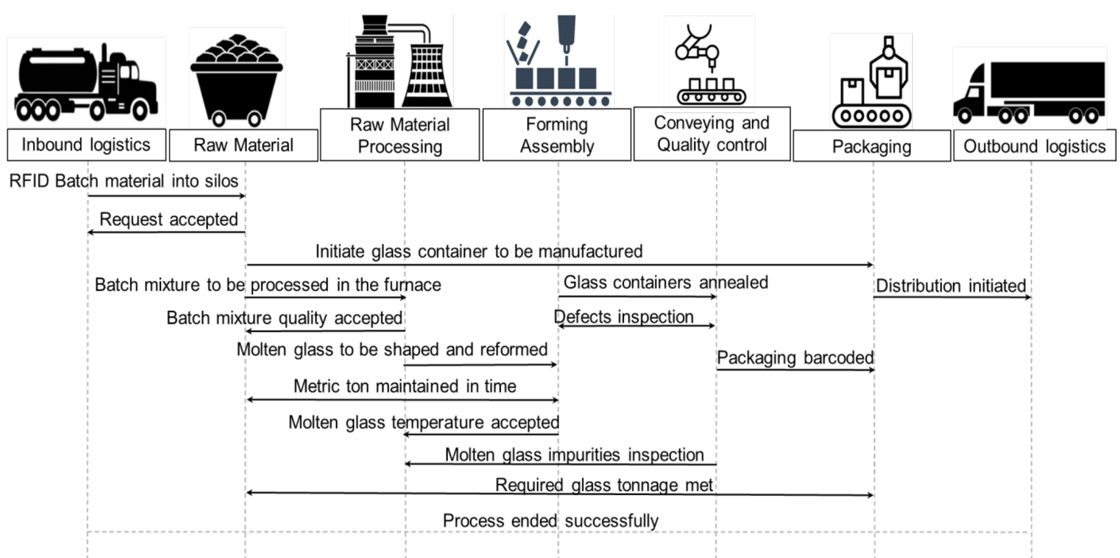


Figure 4. Adaption of TRU in a glass manufacturing process (Reddy, Kurnia and Tortorella 2022)

In the case study, one of the methods of utilizing traceability in blockchain would be to apply it in systems such as Traceable Resource Units (TRU). In manufacturing, Traceable Resource Unit (TRU) is a unique foundational method used for traceability systems to identify and track and trace material and product throughout the value chain. In this case study, the TRU is set to track the glass manufacturing process from each specific batch of raw materials, the produced items, the quality assessment and packaging of the final product. Utilizing TRU's allows the organization to track at a granular level which would enable the organization to locate, recall and analyze all released batches (Reddy, Kurnia and Tortorella 2022).

The system carries essential data enabling organizations to monitor the history, location, and application of items (Kamilaris, Fonts and Prenafeta-Bold´u 2019). Manufacturers can use Traceable Resource Units and blockchain to establish more robust traceability systems, enhanced quality control measures, streamlined operations from downstream to upstream and improved value chain transparency. Traceability systems use technologies like barcodes and RFID to track TRUs in the manufacturing value chain. Figure 5 illustrates interaction of smart contracts among different participants of the manufacturing chain. RFID and Barcodes are common ID technologies in manufacturing. Most traceability systems require global standards software and systems for interoperability in a value chain (Gartner, et al. 2021). The inbound raw material from external suppliers is received at a weighbridge and tagged using RFID cards which describe in detail the type of material, the source, quantity and quality. The request to deliver is sent to the batch plant and the confirmation is accepted with the delivery silo. The blockchain smart contracts would timestamp and document the transactions. Figure 6 shows an example of a blockchain smart contract from the weighbridge to the raw material batch plant.

```
blockchain.py ●
C: > Users > Gcina > simulation > blockchain.py > Block > data
class Block:
    def _init_(self, no, nonce, data, hashcode, prev):
        self.no=no
        self.nonce=nonce
        self.data=data
        self.hash=hash
        self.prev=prev
    def getStringVal(Material=1):
        return Self.no, Self.nonce, Self.data,Self.hashcode,Self.prev
    def data(self, Sand,SodaAsh,Limestone,Dolomite,MinorMaterials):
        self.Sand=1
        self.SodaAsh=2
        self.Limestone=3
        self .Cullet=4
    class Blockchain:
        def _init_(self):
            self.chain=[]
            self.prefix="0000"
```

Figure 5. Example of coding a blockchain smart contract using Visual Studio Code

Table 1. Examples of Ganache hash keys produced from the code

Hash Code Addresses	
Inbound logistics	0x760421Cf7995Be34c4ce9243e5658278181Bf71a
Raw material	0x6803069Aeef184a3D3F026e83301fca7e2e98aCE
Material processing	0x0C041141Ab7Bed37d4bB662d8B8408402F4e3cbD
Forming / assembly	0x283eaEDf298Dc7E910A0b1e66b15AF335c0DB365
Quality control	0xeEF5829Bbd69eac60F919AFa16C5f532A9E54F89
Packaging	0x3d12A24f13b37ec3b268cEF8259801f6b14Db59d
Outbound logistics	0x42f50A1607B2c90C40D0E996FEEB7105697aF5Ce

Once a contract is initiated to manufacture the required glass container, the process is initiated by moving the batch material to the furnace. The smart contract between the two sections carries the hash key as shown on Table 1. With the contract, there is constant monitoring of the process variables and quality of the batch material. The assembly process forms the glass container, and the smart contract documents the process variables and defects from the assembly process. The process is continued throughout the value chain where it is monitored on the smart contract and re-evaluated continuously for quality control. On the final stages, the packaged material is barcoded with a label and dispatched to the customer.

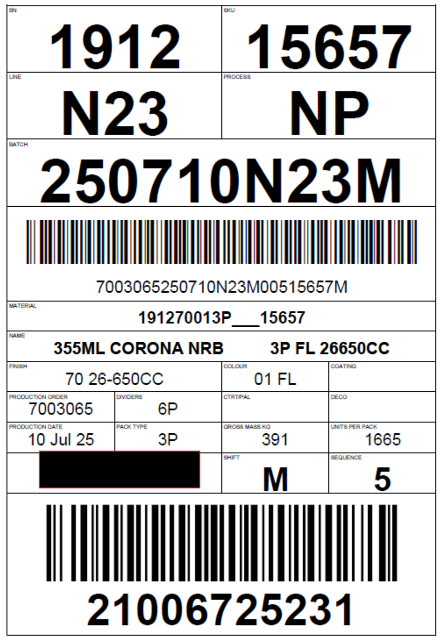
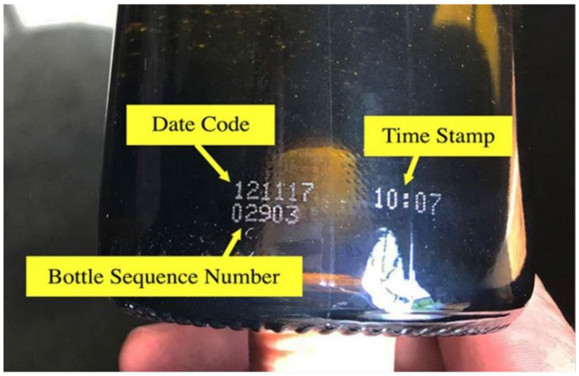


Figure 6. Barcoded label produced to identify each pallet of glass bottles from the process

5. Blockchain traceability in manufacturing

Smart manufacturing uses technology like IoT to improve efficiency by automating processes and analyzing data. The traceability characteristics of blockchain technology assist in managing the inventory required for the production process (Caiado and Quelhas 2020). Smart contracts in blockchain are automated tools that execute pre-programmed agreements on a distributed ledger (Alharby and van Moorsel 2018). These contracts create efficiency in manufacturing by increasing the rate of exchange of information in a secure manner. Smart contracts also support sustainability, risk management, and improve security in IoT devices (Ouyang, Wang and Yuan 2019, Rahman, et al. 2019). From the case study on Table 1, each transaction from between the sections is accompanied by a hash code that is immutable. Tracking and tracing is crucial for manufacturing efficiency, traditionally as indicated earlier barcodes are technologies that are used to capture and store information about the product (Leng, et al. 2021, Wang, Han and Beynon-Davies 2019).

IoT sensors form the first layer of blockchain technology manufacturing control connects machines through industrial Internet technologies which collect data using hash functions syncing the data (Figure 7) between physical machines and cyber systems (Lu 2019). Blockchain technology uses computing, networking and cryptography along with hardware to create a write-once database that stores data in blocks. This helps machines communicate and collect real-time data through IoT, improving transparency and product quality. (Lei, et al. 2017, Kapitonov, et al. 2018). In a glass manufacturing process, the bottle is inscribed with the bottle sequence, data and time stamp that have the manufacturing process for the required bottle as indicated in figure 7. In the third layer involves process monitoring using smart contracts and edge computing with blockchain (Leng, et al. 2021). Traceability resource units systems form a critical layer for blockchain tracking and tracing capabilities (Eryilmaz, et al. 2020).



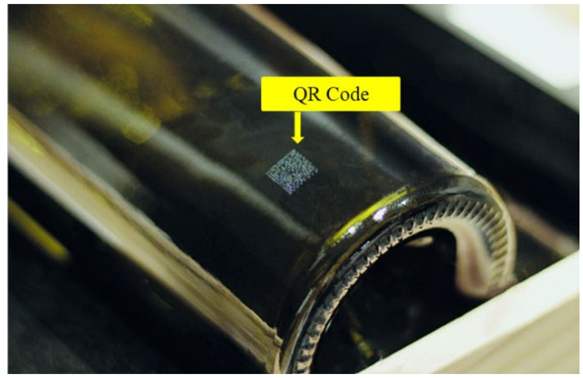


Figure 7. Bottle code marking and QR code marking for product traceability

6. Blockchain benefits and limitations

Product manufacturing refers to a holistic process where raw materials are processed to finished products, in which appropriate plan procurement is executed and the finish product driven by demands and orders (Tao, et al. 2018). There are several benefits of blockchain technology when applied to the manufacturing process. Blockchain technology traceability system shows multiple potential benefits, such as the following: Increased reliability of information security by supporting security features and smart contracts, automating processes and reducing machine downtime and costs halts (Babich and Hilary 2020). Enhanced trust in the traceability manufacturing value chain and enhanced sustainability and transparency (Khwanchol, Tsusaka and Anal 2022). Blockchain enables manufacturers in this case to manage inventory efficiently and assist with reducing costs. All transactions can be confirmed by relevant participants along the manufacturing value chain in real-time through blockchain technology (Park and Li 2021).

The proposal to use blockchain has potential limitations. Addressing these drawbacks requires innovative solutions and better integration strategies. Scalability is a key issue for blockchain technology as the network grows with more users and transactions which lead to slower network speeds and inefficiencies (Mendling, et al. 2018). Solutions like the lightning network are being explored. Integrating blockchain into the current systems can be difficult, which requires significant changes that are costly and time consuming. Blockchain networks consume a lot of energy which demand high energy therefore making blockchain less eco-friendly (Sedlmeir, et al. 2020). The complexity of blockchain also creates barriers due to a lack of understanding which is hard for non-technical users and organizations to adopt (Bracci, et al. 2022).

In the event an organization is running multiple blockchain networks, interoperability is difficult since each network uses its own protocol (Ren, et al. 2023). Organizations also feel uncomfortable with the lack of control in decentralized networks. Implementing blockchain can be costly due to infrastructure needs and the expertise required which can be a hurdle for emerging organizations (Marsal-Llacuna 2018). Managing private keys to run the manufacturing process requires cost investment necessary for securing blockchain assets to fight threats like 51% attacks that pose risks (Tredinnick 2019). Blockchain networks become slower than traditional databases due to its consensus mechanisms which is a drawback in situations where speed is crucial. Lastly, the expanding storage needs to increase as transactions increase which create operational challenges process (Pinheiro, Santos and Barbosa 2019). Efficient data storage solutions are vital for scalability and functionality. Regular maintenance of blockchain networks is resource intensive.

7. Discussion

Looking at the research case study, blockchain and IoT technologies are beneficial for traceability in a manufacturing value chain. The characteristics of blockchain technology as proposed are a viable option for glass manufacturing and manufacturing at large where they support data collection for the purpose of decision-making and quality evaluations. Using the advantages of blockchain technology, the proposed system provides improvements to the mutual consensus mechanism, system reliability, and traceability efficiency. Therefore, the advantages of implementing the proposed system can be summarized as follows: (i) secure and reliable traceability system throughout the distributed value chain, and (ii) intelligent quality evaluation from inbound to outbound logistics. The research studies investigated on traceability describe the principle of traceability in several types of industries. In industrial applications, TRU refers to the smallest uniquely identified unit of a batch during the production process. Traceability depended on the defined relationship between these units as the chain of communication is exchanged between them. These authors agree on the view that there should be a special focus is on the unique identification number of the product in production by placing a unique identifier with information linking these units. The authors suggest that traceability should consist of six elements, product traceability, process traceability, genetic or composite traceability, input traceability, tracking traceability and measurement traceability (Khan, et al. 2018).

8. Conclusion

The search investigated the application of blockchain in a manufacturing organization looking at specifically blockchain as an artifact and traceability as a sub-unit of blockchain. The research looked at a glass manufacturing factory as a case study to track and trace information from downstream to upstream of the manufacturing process. The proposed hypothesis was to leverage cryptographic fundamentals underlying blockchain technology and its smart contracts to achieve tamper-proof logs of events to achieve automated recordings of events that are accessible to all participating stakeholders. The case study illustrated that the proposed usage of blockchain technology would be a technical fit to the current production structure of a glass manufacturing facility in executing the different functions that are triggered in the value chain and implementing them within the blockchain smart contract. The research moreover touched on the security aspect beyond the traceability characteristics of blockchain technology by showing the ability to protect against malicious attempts targeting is integrity, availability and non-repudiation of transaction data which is critical in complex manufacturing processes. As academic and industry advance in technological research studies, the industry is realizing the enhanced capabilities of blockchain to extend the current traceability resource unit systems to achieve end to end transparency and verification of future manufacturing processes.

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