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TruCert: Blockchain-based trustworthy product certification within autonomous automotive supply chains☆

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ABSTRACT

Supply chain networks are complex structures which introduce significant challenges regarding transparency in production and traceability of components, making product certification non-trivial. Visibility within quality assurance processes is critical to this and is particularly important for autonomous & driver-less vehicles which rely on correct operation of individual parts (in the absence of human intervention) to achieve safety of such vehicles. Failure to ascertain quality assurance of parts can result in rogue behaviour among driver-less vehicles which can result in a risk to human lives. In this paper, a blockchain-based approach - *TruCert*, is proposed which achieves trustworthy product certification through enhanced visibility within tier 1 and beyond for complex automotive supply chains. Leveraging blockchain technology, TruCert's potential to improve product quality assurance is demonstrated whilst also strengthening supply chain resilience to combat risks and uncertainties. Utilising the use-case of autonomous connected vehicles manufacturing, design and development of TruCert solution is presented including detailed system design, data model, and smart contracts & oracle implementations. TruCert enables trustworthy part certification across supply chain beyond tier 1 whilst achieving interoperability with heterogeneous systems across suppliers and other stakeholders. Outcomes of evaluation with respect to cost, performance, and security are also presented which highlight the effectiveness of the approach whilst identifying directions for future work.

1. Introduction

Supply Chain Traceability (SCT) is increasingly viewed as the major criteria for competitive advantage of a supply network [1] of an original Equipment Manufacturer (OEM). Hopkins [2] identifies tracking and tracing as the key to enhanced visibility across the supply chain network. It is critical for firms to be able to have increased visibility, which can be achieved through enhanced relationship intensity of suppliers and focal firms ranging from cooperation to coordination to full collaboration [3] in an end-to-end supply chain. However, globalised supply chain networks makes their management and control more difficult [4,5]. Moreover, diverse regulatory policies, and varied cultural and human behaviour in supply chain networks make it non-trivial to evaluate information and manage risks [6,7]. These issues lead to growing uncertainty between business partners which increases the importance of trust within the supply chain network [8–10]. To address the trust shortage and build a stronger relationship between

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the focal firm and the supplier network, there is a real need for trustworthy information sharing, and verifiability of records across the end-to-end network.

In Automotive industry, outsourcing plays an important role in managing both capacity and capabilities across the supply chain network; which results in increasingly complex and dynamic supply chains. This structure has led to a situation where records of sub component parts are distributed across a wide network of suppliers' databases, and the focal company does not own the records of some major components in the vehicle. This low level of record ownership or integration between suppliers and focal company illustrated in Fig. 1, a typical albeit simple automotive supply chain, leads to number of challenges with regards to inefficient transactions, fraud, and quality assurance which affect customers' trust [11,12]. For instance, due to the emergence of the new driver-less technology with heavy reliance on the vehicle safety systems for success of such technologies, the safety and reliability of parts used in manufacturing such vehicles is fundamental to their safe road use. In this context, maximum level of visibility i.e., traceability is a key differentiator which plays a vital role in today's automotive industry. It enables manufacturer to view the records of all parts in a vehicle, both frontward and backward movement [13] of physical entities in the supply chain network including outsourced components for enhanced traceability.

Transparency in supply chains can be defined as the extent to which all stakeholders have a shared understanding of, and access to, the product related information that they request, without loss, noise, delay and distortion [14]. Traceability represents the ability to access specific information about anything that remains as part of a supply chain including products, processes or member of the supply chain like suppliers and retailers.

1.1. Problem statement

A number of established enterprise solutions help streamline supply chain processes such as Enterprise Resource Management (ERP) systems, and Manufacturing Execution Systems (MES), however the visibility provided by such systems is limited to 'tier 1' suppliers. The blind spot left by these systems limits the ability of a modern manufacturing organisation in many ways. Firstly, it limits the business's ability to estimate lead times for materials, which consequently affects product delivery to customer. Secondly, the lack of materials traceability hampers the business's ability to record provenance, which is significant with respect to mitigating counterfeit products as well as in achieving responsible manufacturing. Finally, the lack of supply chain visibility also affects the business's ability to achieve standardisation across the supply chain especially for make-to-order products where adherence to custom design specifications is critical to success.

Although the above challenges are valid for a typical modern manufacturing organisation, their significance is heightened for autonomous vehicle supply chains primarily due to their reliance on correct function of parts to achieve a safe operation. Specifically, visibility into the quality assurance processes adopted at a supplier is required to ascertain compliance with standards and processes, leading to manufacturer's confidence in safe use of the vehicle. In the absence of such measures, a manufacturer's ability to certify safe operation of autonomous vehicles is limited which affects adoption of this cutting-edge technology.

Since the introduction of Bitcoin in 2008, *blockchain* - known as a technology for achieving distributed storage of records - has gained tremendous popularity among various industries. blockchain is considered as the next disruptive technology under the umbrella of Industry 4.0, and it has assimilated impacts to the internet [15]. By design, it has several attractive features such as immutability, disinter-mediation, transparency and anonymity which make it a great fit for addressing the challenges current supply chain systems face. This shows the potential blockchain technology has to reshape how supply chain is managed. The decentralised storage of records using blockchain brings different advantages to supply chain processes including transparency, reliability, audibility and efficiency in both time and cost.

The blockchain & supply chain integration is gaining much interest from both academia and industry. A number of efforts such as [16–21] have been made which leverage blockchain technology to address challenges faced by supply chains. However, these are limited in terms of visibility they provide for supply chains, granularity of data captured, engagement with stakeholders, and integration with legacy processes and systems. In this paper, TruCert - a blockchain-based supply chain traceability solution is presented to enhance visibility within complex supply chains in a trustworthy manner. TruCert solution aims to achieve end-to-end traceability of supply chain products by: firstly, developing a Hyperledger Besu based consortium blockchain which involves all relevant stakeholders; secondly, real-time data about parts throughout their journey by utilising IoT devices; and, finally, utilising the traceability information to develop trustworthy product certification.

TruCert implementation includes usable user interfaces to facilitate end users and to achieve interoperability with existing systems and processes. For instance, standard quality assurance processes devised to ensure safety of lithium batteries involve inspection by an accredited third party which produces a good safety certificate. TruCert enables uploading and attaching such digital documents through usable interfaces to ensure comprehensive data records. In view of the sensitivity of the data and processes involved, TruCert uses consortium blockchain (Hyperledger Besu[1]) to record part traceability data. Stakeholders such as the manufacturer and its suppliers are envisaged to host blockchain nodes which are part of this blockchain. Further, smart contracts and a proprietary oracle are developed to facilitate recording data from off-chain systems and processes on the chain. Smart contracts and the oracle provide an API to achieve interoperability which enables their use for emerging use cases such as track & trace by third-parties, digital Certificates of Conformity (CoC), and digital twining for process optimisation. Although the case of automotive supply chains is used in this paper, TruCert can be adopted to wider industrial domains such as food, agriculture, and pharmaceutical. TruCert model analyses using smart contracts to enhance business efficiency whilst minimising errors and delays in the ordering workflow.

[1] https://besu.hyperledger.org/en/stable/

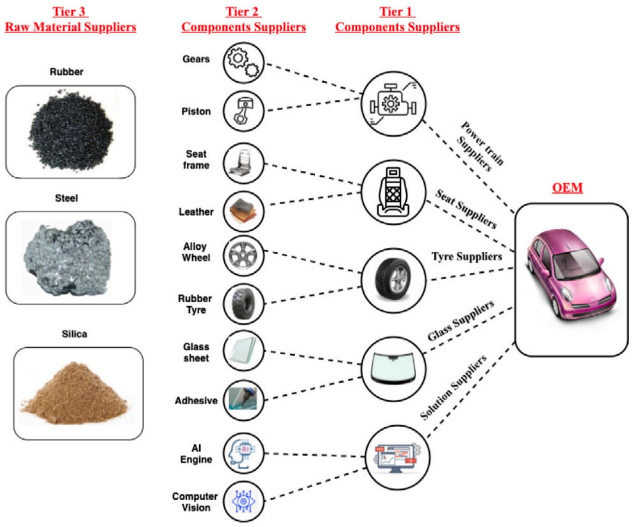

Fig. 1. Typical automotive supply chain [22].

1.2. Major contributions

Major contributions and practical implications of this work are threefold:

- First, we demonstrate the feasibility of a blockchain-based solution with visibility as a core feature in the domain of automotive industry supply chain. We highlighted the problems facing this industry such as lack of traceability, lack of transparency, lack of trust, counterfeit items and others and how to overcome these problems by switching to a blockchain-based solution.
- Second, by exploring blockchain technology from a technical perspective, we generate generalisable knowledge and insights about how to integrate blockchain into supply chains in general which would help researchers and industrial partners.
- Third, through our prototype, we share technical details which enable participants to gain insight into an efficient building process and enhance their understanding of blockchain and associated benefits of its use.

The rest of the paper is organised as follows; Section 2 provides an overview of emerging supply chain, blockchain technology, and asset tracking. Related works regarding use of DLT for part traceability in supply chains is summarised in Section 3. TruCert model is explained in details in Section 4. Details about TruCert model implementation is explained in Section 5. In Section 6, model evaluation is summarised followed by threats to validity in Section 7. Finally, our work is concluded in Section 8.

2. Blockchain and emerging issues in supply chains

2.1. Need for certification within automotive supply chains

Automotive Industry is one of the world's largest industries by revenue [23]. It consists of a wide range of companies and organisations involved in the design, development, manufacturing, marketing, and selling of motor vehicles. Effective supply chain management is a key challenge in modern automotive industry especially due to lack of visibility therein.

Compared to other systems, the supply chain in the automotive industry is considered as less responsive, integrated, and visible [24]. The complex architecture and lack of transparency in transactions between participants involved are the primary reasons behind this. One of the main challenges facing current traceability applications in automotive industry is their centralised architecture which introduce a single point of failure while also introducing concerns with respect to trustworthiness of information shared as highlighted by [25]. Thus, its very important albeit non-trivial to create a decentralised trust mechanism and effective systems for trace and tracking to ensure the information linkage between all supply chain participants [26].

In order for a vehicle to be *road worthy*, the manufacturer has a legal responsibility to confirm that the vehicle meets all applicable regulatory standards and specification. For this purpose, Type Approval/ Homologation or Self-Certification, or a hybrid approach can be used [27]. Specifically, type approval is a confirmation that production samples of a particular design will satisfy the legal requirements of the market. In EU, there are two methods for type approval; the first one is based on EC Directives and the other one is based on United Nation Economic Commission for Europe regulations (UNECE). Type approval describes the process applied by national authorities to certify that a type (model) of a vehicle meets all EU safety, environmental and conformity of production requirements before authorising it to be placed on the EU market. Type approval makes a distinction between *components* of vehicles such as lightening and view mirrors and *systems* of vehicles such as breaking, crash performance and emission. Due to this distinction, two types of approvals are required; Component Type Approval and System Type Approval. The former is designed to prove a

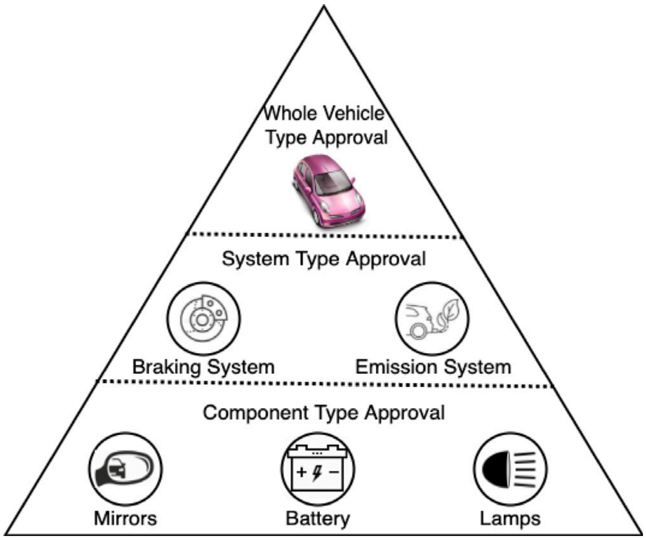

Fig. 2. Vehicle approval levels.

component may be fitted to any vehicle while the latter is based on the previous one and focuses on approval of a set of components or a performance feature of a vehicle.

Once all of the relevant system and component approvals are in place, the vehicle will be considered as a whole by a designated approval body or authority. This assessment can take place at any appropriate facility, providing the appropriate equipment and environment are available. Submission of relevant manufacturer's information document including reference to several type approvals of all systems and components will result in the issue of a *European Whole Vehicle Type Approval Certificate (WVTA)*. Once a vehicle is approved, the manufacturer is able to produce a Certificate of Conformity (CoC) for each vehicle manufactured. CoC is a certificate issued by an authorised trusted party such as manufacturer or an independent laboratory which confirms that a particular product meets a set of standards or specification in a particular industry. CoC can either be created for a specific part such as a battery or for a vehicle (see Fig. 2).

Since OEM requires each part within a vehicle to have a valid CoC, its important to share information between OEM and manufacturers about these certificates. However, this process is subject to several drawbacks such as delays, sharing invalid certificates and others. Towards addressing these drawbacks, we provide a digital representation of CoCs and other certificates in a distributed real-time environment. This digital representation has the following characteristics:

- Verifiable: to enhance trust in CoC and the whole system as well, CoC should be verifiable. Verifiability means the ability to check whether the CoC has been changed or not at any time. This is achieved by using a distributed off-chain storage and adding the uploaded CoC's hash identifiers to the blockchain immutable ledger.
- Authentic: it is crucial in digital platforms to check the authenticity of documents to make sure it is issued by trusted parties. A particular CoC can be issued by corresponding manufacturer.
- Specific: a particular CoC should be issued only for a single vehicle/part and demonstrates that the vehicle/part is manufactured according to standards and specifications and passes the required safety tests.
- Valid: a CoC should be valid in terms of tests applied and their approval.

2.2. Blockchain technology

Blockchain technology- a particular type of Distributed Ledger Technology (DLT)- has received much attention after the introduction of Bitcoin cryptocurrency in 2009 [28]. As the name suggests, it is a chain of inter connected blocks which hold information with digital signatures in a distributed manner. These blocks are connected to each other using cryptographic hash functions. Each block acts as a container holding entries called transactions which represent the transfer of digital assets between participants within the network.

As shown in Fig. 3, each block consists of two parts; the block header which contains several parameters and block body which contains the actual transactions within the block. Blockchain relies on consensus mechanisms to maintain the integrity of its data which makes it possible for participants to operate in a trustless environment. The decentralised architecture of blockchain eliminates intermediaries and supports direct transaction verification among participants [29]. Further, using cryptographic primitives reduces the risk of losing and tampering with data and prevents any human errors in transactions. This enables network participants to securely share, access and verify information on blockchain [30]. These features enhances the reliability and trustworthiness of supply chain operations and activities and efficiently simplifies decision-making process [31]

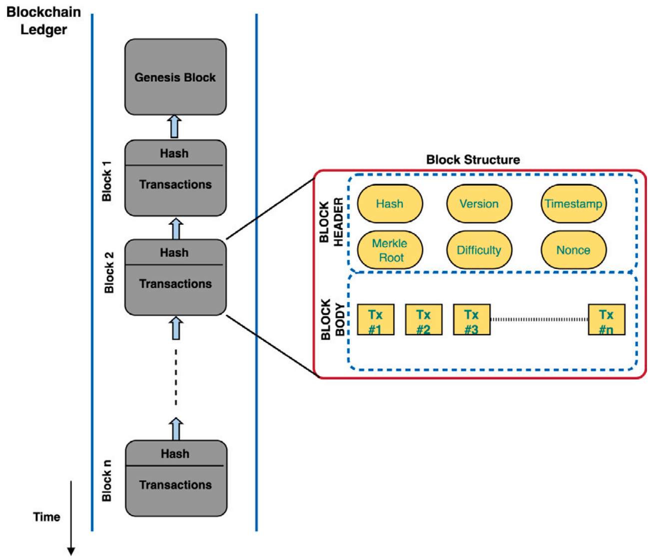

Fig. 3. Sample blockchain structure.

Blockchain has an inherently distributed architecture with distinguishing characteristics such as data integrity and tamper-resistance. These characteristics have enhanced the potential of blockchain technology to be exploited beyond cryptocurrencies in different areas including electronic voting [32,33], supply chain management [6], electronic health record management [34] and others.

Blockchain systems can be classified into three types: Public, Consortium and Private blockchains [35]. Public blockchain can be accessed by anyone who has access to the internet. This type is used by the majority of digital currencies. The main advantages of this type are transparency and auditability of data, but it has some challenges related to data privacy and performance. In consortium blockchain, a network is created across multiple organisations where the consensus mechanism is controlled by a pre-defined set of nodes. A private blockchain is controlled by one organisation and participants need to be authorised before they become able to join the network. Being governed and controlled by a single organisation makes private blockchains flexible for configurations.

2.3. Asset tracking technologies

Asset tracking in supply chains is a complex task especially when these assets are located in diverse physical settings and are susceptible to mobility across vast geographical locations. One of main challenges at such situations is the lack of connectivity at some locations which adds complexities on tracking these assets and be aware of the environmental conditions around them. A comparative analysis of asset tracking technologies used within supply chains is summarised in Table 1 and explained below.

- **Barcode**: Barcode is one of the most common tools used for assets tracking. In barcode, data is represented in a visual, machine-readable form. Data can be represented by using varying widths and spacings of parallel lines. Barcodes, can be scanned by special optical scanners, called barcode readers and have been used in supply chain management for many years. Although barcode is the cheapest and easiest option among tracking tools, it is based on 'line-of-sight' which requires each item to be manipulated one at a time, reducing the efficiency of reading process.
- **QR Codes**: Quick Response (QR) code is a common medium for effective data transmission. A QR code can hold up to 2956 bytes of payload which makes it useful in various fields such as product tracking, advertising, authentication, payment, and others. Interacting with QR codes is done using cameras allowing users to use their smart phones cameras to read the code. QR codes are subject to several attacks which mainly aim to embed malicious content as payload to either steal credentials or break privacy by redirecting users to malicious websites or installing malware on their devices.
- **RFID**: Radio Frequency Identification (RFID) tags are used to store information and transmit it over radio waves. Tags content can be scanned and read easily using RFID scanners once they are close to each other. RFID is advantageous because it does not require line-of-sight scanning, it acts to reduce labour levels, enhances visibility, and improves inventory management. RFID tags can be categorised into active and passive depending upon availability of the power source. RFID tags are advantageous for assets tracking as: (i) the data stored in tags can be encrypted to provide enhanced security, (ii) the tags can store much more data than other methods, and (iii) RFID tags can be read all at once, rather than one at a time, by the scanner.
- **IoT Devices**: Internet of Things is a network of physical objects (things) which are embedded with sensors capable of capturing data from the environment for the purpose of connecting and sharing it with other devices and systems on the internet. IoT has the potential to support supply chain management systems in many areas such as product tracking, operation visibility, supply

Table 1
Assets tracking technologies.

Features	QR Codes	RFID	IoT
Reading	Line of sight	Non line of sight	Non light of sight
Cost	Low	Moderate/High	Moderate/High
Data	Basic	Basic	Comprehensive
Setup	Easy	Easy	Complex
Transmission	Passive	Passive/Active	Active

chain visibility and performance. As IoT is a wireless technology, its applications are built using many sensors connected and sharing data with each other. This architecture poses concerns regarding security and privacy of data and scalability of the system.

3. Related works

Distributed Ledger Technologies and blockchain in practical have become a spotlight for both academia and industry recently. There has been an explosion of interest in the application of distributed ledger technologies in supply chain area [6,36] which results in an increasing number of relevant researches being published on one hand and several industrial solutions such as IBM[2] and Everledger[3] on the other hand.

Several blockchain-based traceability models focusing on different aspects of supply chains have been proposed in the literature. Kuhn, Funk, and Franke [37], proposed a blockchain-based traceability solution focusing on the production history of complex product configurations. Their model uses consortium Ethereum blockchain network with PoA and focuses on the production perspective where physical manufacturing entities including machines and devices are represented on blockchain by assigning an account to each one of them. Their traceability solution relies on representing physical entities using ERC 1155 tokens.

Omar et al. [38] proposed an blockchain-based generic tracking framework utilising smart contracts and distributed storage to automate the processes and exchange of information in Personal Protective Equipment (PPE) supply chains during the COVID-19 pandemic. Their solution uses Ethereum blockchain to ensure end-to-end traceability of each PPE while maintaining quality assurance. Each PPE is identified using a unique product ID which is used by authorised stakeholders to track details in real-time. Liu, Barenji, Montreuil, and Huang [39] proposed a smart tracking and tracing platform to provide a decentralised traceability solution in the drug supply chain. Their solution consists of a unified five-layers; perception layer dealing with IoT devices for sensing, off-chain layer storage for large data storage, blockchain for tamper-proof and transparent decentralised storage, application layer for providing different services such as identity management and risk analysis and user layer where different stakeholders take place. However, security evaluation of their platform was not completed. Sunny, Undralla, and Pillai [40] highlighted the possibilities of blockchain traceability solutions for achieving transparency in supply chains. Utilising cold chain as a use case, a proof of concept was presented using Azure Blockchain Workbench which provides a Proof of Authority (PoA) Ethereum network.

Miehle et al. [41] authors presented PartChain as a decentralised application for achieving traceability of automobile parts. The major participants of their solution are OEM, suppliers and logistic service providers. Their solution enables the creation, monitoring, and sharing of a unique digital representation of a physical part across a supply chain in a premissioned blockchain (Hyperledger Fabric) using tokens where the ownership could be transferred via mobile application. This facilitates defective parts traceability and helps to eliminate the counterfeit parts.

Upadhyay, Ayodele, Kumar, and Garzareyes [42] conducted a review of the challenges and opportunities associated with blockchain technology adoption from the lens of the technological–organisational–environmental (TOE) framework in the UK's automotive industry has been conducted. The authors highlighted the managerial implications and insights that help companies such as car makers using this technology.

Lu et al. [43] proposed a blockchain-based counterfeiting prevention system for automotive supply chains by tracking and tracing the part's details through RFID or QR code. They investigated the role of DLT in automotive supply chain and the benefits it could bring such as improving containment of defective components and enhancing track and traceability across the sub-tier network. Their proposed model uses Hyperledger Fabric network where suppliers, OEM and dealers act as endorsing peers to maintain the same complete ledger of the network. In their model, for each network participant a set of roles and actions is introduced. Further, they introduced car as a self-aware entity which is capable of interacting with the blockchain network to verify the mounted components. However, the cost analysis of the their system is not presented

Patro et al. [44] proposed a blockchain-based product recall management model in the automotive supply chain. Their model aims to overcome different problems related to product recall management including transparency, traceability, security, and trust. They employed the public Ethereum blockchain and integrate it with the decentralised storage of the InterPlanetary File System (IPFS) to deal with the large-sized data such as certifications and inspection reports. The blockchain network consist of several actors including dealers, customers, automakers, inspection department and others. Interaction with the blockchain is

[2] https://www.ibm.com/blockchain/supply-chain
[3] https://everledger.io/

accomplished through using three smart contracts; registration, recall handler, and inspection handler. Authors claim that their model is cost-efficient, however, as recall and inspection requests increase the total cost will increase which would result in a costly model.

Choi [45] used Blockchain technology in luxury supply chains for diamond authentication and certification. Their approach aims to address the challenges facing classical paper-based diamond certification process such as forgery and data unclarity by building formal analytical models to explore the values of Blockchain technology. However, the work lacks in-deep details about how Blockchain technology is used.

Further, Munoz, Zhang, Shehzad, and Ouhimmou [46] proposed LogLog; a Blockchain-based system reliable with The Forest Sustainability Council (FSC) certification standards using smart contract on top of Ethereum Blockchain for tracking wood volumes throughout a supply chain. Their model demonstrates the capacity of DLTs to express complex domain-specific validation logic related to the forest industry by providing two implementation references using ERC-721 and ERC-1155 standards. Even thought high level of trust can be achieved by building the system entirely on chain, the cost associated with minting tokens and transferring their ownership is a big challenge for adoption.

3.1. Comparative analysis

The present literature review provides an analysis of the adoption of blockchain technology in the supply chain domain. The majority of studies in this area focus on the conceptual development of blockchain applicability in supply chain systems. Prior research studies, including [16–21], concentrate on leveraging blockchain to enhance supply chain visibility; however, they lack detailed technical information and do not provide a solution to address the challenges associated with blockchain adoption. Specifically, these studies often fail to provide concrete implementation details, evaluation, and do not investigate the use of private permissioned blockchain networks. The common theme among these studies is the identification of problems faced by supply chain systems and proposing a blockchain-based solution to address those problems.

The main focus of industrial solutions is primarily on creating new business opportunities for sales. Both academic and industrial studies utilise certain properties of blockchain technology or opportunities associated with its adoption, such as trust, transparency, traceability, and immutability of records, to develop their proposals and solutions.

Conversely, TruCert solution aims to achieve end-to-end traceability of supply chain products by firstly, developing a Hyperledger Besu based consortium blockchain which involves all relevant stakeholders; secondly, real-time data about parts throughout their journey by utilising IoT devices; and, finally, utilising the traceability information to develop trustworthy product certification.

4. TruCert - A blockchain-based trustworthy product certification within autonomous automotive supply chains

In this section, details of the TruCert solution are presented which is aimed at achieving part certification through trustworthy traceability in automotive supply chain systems. Although the focus in this paper is on application of the TruCert solution within autonomous automotive industry, it can be adapted to wider domains such as food, agriculture and pharmaceuticals.

4.1. Vision

Compared to other industries, safety within the automotive industry is very sensitive as lack of safety can result in adverse impact on human lives. The impact is aggravated with the introduction of autonomous vehicles as these tend to be driverless with limited human intervention.[4] In this respect, OEM is expected to meet all safety regulations before a vehicle can be declared *road worthy*. This includes ensuring that all parts of a vehicle are certified and all the required tests are passed before they can be shipped. Due to the complexity of manufacturing supply chains, achieving this objective is a non-trivial challenge as the processes are spread across multiple suppliers and geographical locations. In this context, enhanced visibility within complex supply chain systems is the missing piece which can facilitate quality assurance across diverse organisations.

Further, to achieve sustainability, its important to have the confirmation and verification that processes, products and activities within the supply chain meet certain sustainability criteria. This requires improving different aspects of supply chain such as security, transparency, and audibility in order to share information in a secure and trusted manner. Additionally, contemporary supply chain solutions provide limited visibility across supply chains. On one hand, this could prevent business for reaching their optimal goals and impact their ability to estimate lead times for material and raises concerns about trust and data integrity due to the centralised architecture on the other hand.

Inspired by these challenges, *TruCert* is proposed as a blockchain-based solution for enabling end-to-end visibility within the automotive supply chain. The visibility provided by *TruCert* is geared towards achieving safety and quality assurance within the supply chain and contribute to its sustainability. To this end, *TruCert* considers the following added values by enabling visibility within supply chains:

[4] https://www.bbc.co.uk/news/technology-36680043

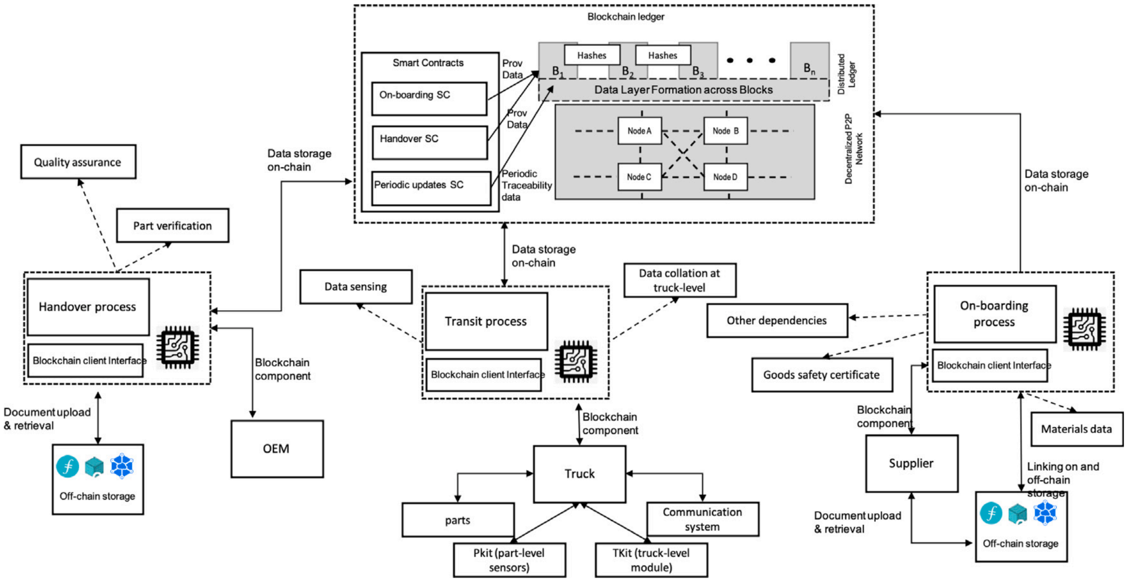

Fig. 4. High-level architecture for the DLT-based part traceability in supply chain.

- **Trust**: integrating blockchain within automotive supply chain eliminates the role of intermediaries which results in maintaining data integrity as it becomes almost impossible to tamper with stored data. Further, the transparency of blockchain enables supply chain participants to trace the full history of a product or a service. This enhances the trustworthiness of the whole system and encourages other participants to join.
- **Cost efficiency**: the recent technological evolution has resulted in a shift towards digitisation of supply chain's processes and activities. The no longer need to use papers and spend long time for verification which leads to saving time and money.
- **real-time data**: providing real-time data about the processes and products within the supply chain facilitates the decision making and helps OEM to gain deeper insight.

4.2. Data model

In this subsection details about data definition model used for providing traceability across multi-tier automotive supply chains by leveraging the DLTs are presented. This contains details about data entities, their attributes, and relations among the entities. The data definitions included in this subsection provide coverage for both on and off-chain data storage.

As shown in Table 2, the data model consists of 13 entities which provide coverage for data about different aspects covering stakeholders and processes within the automotive supply chain. This data covers parts through several phases; On-boarding where parts become ready to be shipped, Transit where parts are placed into trucks to start the journey towards their final destination and Handover where parts reach their destination. Data model deals with a wide range of data related to the parts including parts' details, their manufacturers, certifications, which orders they belong to, shipment trucks and the remote data associated with them and many others. Details about each data entity, its data attribute and relationships with other entities is explained in Table 2.

4.3. TruCert model overview

TruCert model is based on gathering data related to parts through their journey, starting from the moment leaving their origin until reaching their destination. The model covers three main phases (1) Onboarding where parts are put in the shipping trucks before leaving their origin, (2) Transit where parts move between several locations and (3) Handover where parts reach their final destination. Data related to parts at all these phases will be published into DLT where it can be accessed by interested participants within the system. Using DLT for keeping traceability data about parts enhances transparency of the whole supply chain on one hand and enhances trust among participants on the other hand.

In Fig. 4 a high-level architecture of the proposed traceability model is illustrated. It includes details about the different components and their inter connectivity at different phases in order to provide part traceability along the supply chain. The overall traceability processes is divided into three phases i.e. On-boarding, Transit, and Handover. Each of these phases is explained below and illustrated in Fig. 5.

Table 2
Data definition model including description of entities involved.

Entity name	Description
QA Entity	This entity represents Quality Assurance partners authorised to issue certificates indicating the safety of a specific part. Depending on the nature of the part, they can carry out several tests to ensure the safety compliance of a part. Keeping information about those approval partners/advisors on the ledger enhance the trustworthiness that the issued certificates are valid.
Supplier	Suppliers are crucial to provide manufacturer with required parts necessary for POD assembly. This entity keeps different details about each supplier. Leveraging the transparency feature of DLT, in our model suppliers at different tiers would be able to track parts at any given time.
Phase	Each part passes through several phases within the supply chain. Traceability data about parts are recorded on the ledger at each phase. This makes it easier to track a part and view its movement history at a specific phase.
Order	Order data entity represents purchase orders submitted by customers who wish to use PODs from Westfield. Details about each order are recorded on the ledger.
Customer	The Customer entity keeps data about customers who wish to use the PODs from manufacturer. They interact with manufacturer by submitting orders to purchase. PODs. Customers can later query the ledger via programmable interface for tracking the PODs and parts as well.
QACert	Quality Assurance certificates are of utter importance in our traceability model. For parts which require such kind of certificates like lithium batteries, it is necessary to have those certificates in order to accept the part at the transit phase. It is planned to capture documentation related to the quality assurance processes through the use of a bespoke client interface which enables uploading scanned copies of such documents to IPFS. The IPFS addresses are then linked with the blockchain as a transaction to achieve tamper-proof storage.
CoC	Certificate of Conformity (CoC) is a certificate issued by an authorised trusted party such as manufacturer or an independent laboratory which states that a particular product meets a set of standards or specification in a particular industry. In our model CoC can be issued at part-level and POD-level. An individual part can have only one CoC where a POD may have multiple CoCs. Details about CoC are kept in this entity. Through the use of a bespoke client interface which enables uploading scanned copies of CoCs to IPFS. The IPFS addresses are then linked with the blockchain as a transaction to achieve tamper-proof storage.
POD	Pod is the key entity in our model. Pods are autonomous driverless vehicles relying on advanced computing systems for their reliable operations. Pod assembly at manufacturer relies heavily on the timely and correct delivery of the parts the pod consists of. Thus, it is of utter importance to track and trace those parts at any time.
Part	Part is the central entity in our model. It represents the physical parts the autonomous pod consists of. These parts are supplied to manufacturer from several suppliers at different tiers. Its crucial to track each individual part through its journey in the supply chain starting from on-boarding phase, passing through several stops at transit phase until reaching its final destination where handover phase starts. Details about each part is captured via a smart kit responsible for capturing location and other environmental data at periodic intervals which is then broadcasted onto the DLT ledger.
Critical Part	A specific type of part which require specific Quality Assurance certifications and has to follow specific shipment regulations and standards. This entity holds details about the type of the critical part along with a list of Quality Assurance requirements needed for this part. It is important to have these requirements recorded prior to shipping the part.
Truck	This entity represent the trucks which will be used for shipping parts. These trucks are equipped with a smart kit (TKit) which acts as a blockchain client which is responsible for receiving sensing data from parts and broadcasting them onto the ledger. Trucks play an important role in broadcasting traceability data during the transit phase.
Tracking Data	This entity holds data captured from sensors attached to each individual part in a particular truck. These details are grouped together in a JSON object. It also includes a list of parts which exist in the truck at any given time.
Event	Traceability data about parts are kepts as events stored on DLT. At any given time this entity can give details about which parts are in a specific truck along with traceability data captured from sensors attached to those parts.

4.3.1. On-boarding

The on-boarding process is completed at the supplier where the supplier uses a blockchain client interface to record part details including materials data, dependencies, and quality assurance processes on the shared ledger. Such blockchain client will use smart contract and the proprietary oracle to achieve interoperability with blockchain ledger and to upload off-chain data to the blockchain. Further, the supplier uses an off-chain decentralised storage (IPFS in our case) to store documents or certificates which may be created through specific processes such as a *goods safety certificate* for lithium batteries. These documents are linked to the

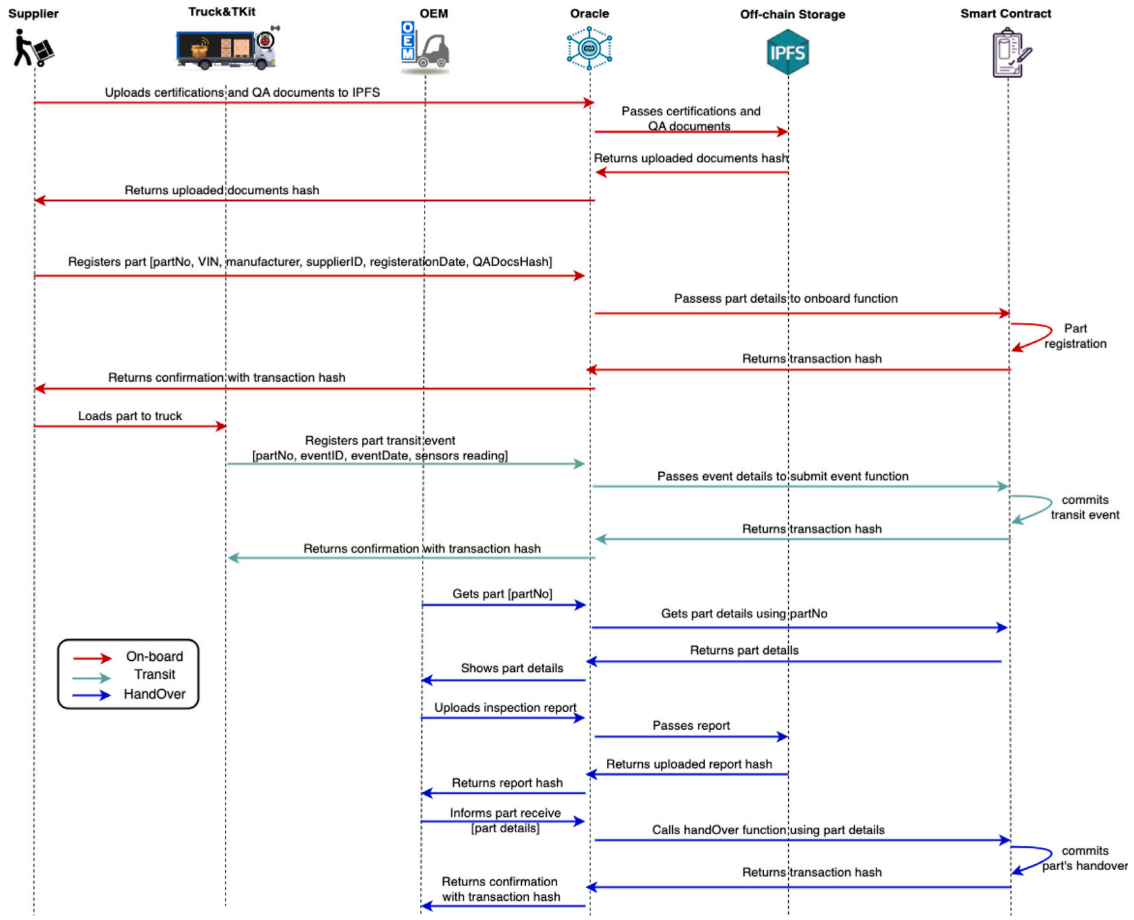

Fig. 5. Sequence diagram showing interactions among suppliers, OEM, smart truck, oracle, IPFS and smart contracts.

blockchain ledger by storing their hash as a blockchain transaction. Our aim to implement blockchain client interface is to facilitate interoperability with legacy systems at the suppliers.

4.3.2. Transit

The second phase of the TruCert solution is to track a part's journey from its supplier to the manufacturer (final destination). As evidenced in Fig. 4, a part is assumed to be carried from the supplier to destination on-board a truck. In order to facilitate the part traceability throughout its journey on the truck, a bespoke blockchain clientis developed which is hosted on a single board computer (*truck module*) and equipped each part with a sensing device. The truck module is able to communicate with the sensing devices mounted on individual parts to gather measurements such as temperature and moisture etc. Further, the truck module has the capability to connect and communicate with the blockchain ledger through a custom, lightweight blockchain client that is able to add sensing data of the parts to the shared ledger at periodic intervals.

Once a part is mounted to the truck, its *partNo* and *macAddress* is recorded in an internal storage controlled by the truck module. The truck module periodically reads the list of stored *partNo*s and establishes a connection with the sensing device attached to that part using the corresponding *macAddress*. Once the connection is established, the truck module will read data from the different sensors in the truck, create a transaction including the collected data from sensors and submit the transaction to the oracle in order to be stored on the ledger.

4.3.3. Handover

Handover represents the final phase of the part traceability system and is accomplished at the manufacturer's factory. When a part reaches manufacturer's factory, it is expected to go through a verification process and a quality assurance process. These processes are envisioned to be captured through an off-chain storage such as IPFS or filecoin. This is because, such inspection and quality assurances processes currently result in a paper document which is important to store. The hash of these records will be added to blockchain ledger to achieve immutable record of parts received at the manufacturer factory. Furthermore, a blockchain client is envisioned to be developed which enables storing part information to the shared ledger.

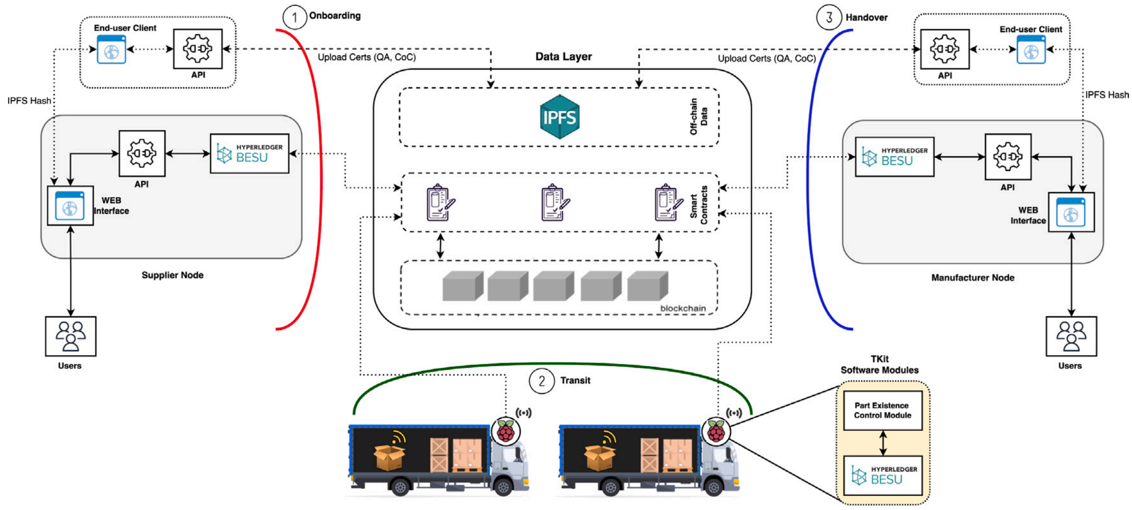

Fig. 6. TruCert model phases and components.

4.4. TruCert model components

As shown on Fig. 6, TruCert model comprises the following components:

- ***Distributed Ledger Layer***: Distributed Ledger Technology refers to the innovative and fast-paced model for storing and sharing data across multiple stores in a secure and tamper-resistant manner. TruCert model uses a private permissioned blockchain network. This choice has an impact on both data privacy, time and cost associated with recording data on the ledger. For building the blockchain network Hyperledger Besu platfom is used.
Hyperledger Besu is an open-source Ethereum client developed in Java under Apache 2.0 licence. It is the most recent platform joins the Hyperledger foundation. Hyperledger Besu can run on the Ethereum public network or on private permissioned networks, as well as on test networks such as Rinkeby, Ropsten, and Görli. Besu includes several consensus algorithms such as PoW, PoA and IBFT and has comprehensive permissioning schemes designed specifically for uses in a consortium environment. It represents the growing interest of enterprises to build both permissioned and public network use cases for their applications. Besu has a couple of interesting features such as privacy and permissioning. In Besu, it is possible to keep transactions private between involved parties while other parties will have no access to the transaction payload. Privacy is achieved by using Private Transaction Manager. Permissioning is about controlling who can join the network and who can do what. In Besu, there are two types of permissioning node and account.
Hyperledger Besu has come to scene to help enterprises addressing the challenges of running their own applications on Ethereum blockchain including data privacy and scalability. Enterprises have very different needs from individual users on a peer-to- peer network. These needs can be organised into four categories (1) permissioning, (2) privacy, (3) performance and (4) finality. Hyperledger Besu meets these requirements by integrating Enterprise Ethereum Alliance (EEA) specifications which are established to create common interfaces amongst the various open and closed source projects within Ethereum, to ensure users do not have vendor lock-in, and to create standard interfaces for teams building applications.
- ***Smart Kit Module (TKit)***: TKit is a software modules which runs on trucks for part shipments within automotive supply chains. This kit is demonstrated using a Raspberry PI. This kit is responsible for two main tasks (1) control the existing part inside the truck at a specific time. This is accomplished by establishing a connection between the Raspberry PI and the Bluetooth tags attached to each part. (2) periodically update the status of each part via oracle. In TruCert, smart kit is equipped with GPS sensor in order to retrieve the GPS coordinates for each part at specific time.
In order for the TKit to accomplish its tasks, two different software are developed. The first one is responsible for keeping track of which parts the Tkit is responsible for. This is achieved by recording the partNo of each part and macAddress of the bluetooth device attached to that part. These details are recorded once parts are loaded to trucks. The second software is developed using Python and is responsible for three main tasks (1) connect to the Bluetooth devices attached to parts, (2) read sensing data from the various sensors attached to the truck, and (3) create a transactions including the obtained details and submit them to smart contract via oracles.
- ***Off-chain Storage***: Interplanetary File System (IPFS) is a storage medium which allows for distributed storage of data that is immune to altering and forgery. The main reason behind using off-chain storage is that blockchain is not suitable for large data storage such as files. IPFS is one of the most suitable storage mediums for this category of data. For each document stored, IPFS returns a unique identifier which is used for retrieving that file. This identifier is very crucial as Data stored on the IPFS network cannot be altered without changing the data identifier. In IPFS, the identifier is a cryptographic hash of the data.

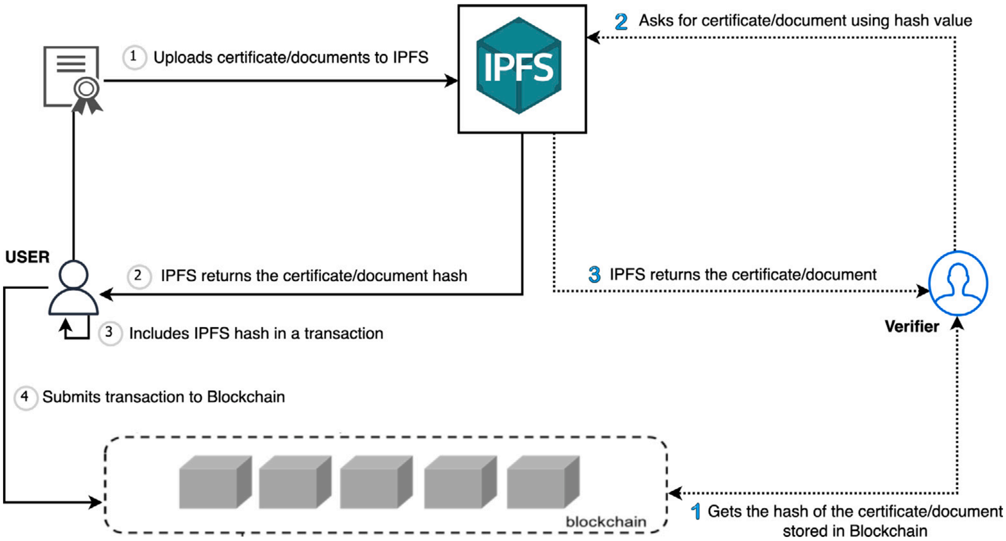

Fig. 7. Data integrity of documents submitted to IPFS.

This means non-critical data can be stored to IPFS while storing this identifier to an underlying distributed ledger. This would result in less exhaustive operations over the distributed ledger.

- ***Smart Contracts and Oracle***: The smart contracts and oracle are concepts within blockchains which enable utilising data stored within a ledger to execute custom business logic as well as interoperability with non-blockchain systems and services. Smart contract is a self-executed programme run on top of blockchain. It allows interacting with the blockchain for either recording data or retrieving data from the blockchain. In order to facilitate interaction of blockchain-based systems with external services (such as off-chain systems and processes), oracles have been introduced. As smart contracts cannot access data from outside their network, blockchain oracles are the services that send and verify real-world occurrences and submit information to smart contracts, triggering state changes on the blockchain. Within TruCert, a proprietary oracle has been implemented to achieve connectivity between on-chain and off-chain processes.
- ***End-users Web Client***: In order to enable end users record data about parts on the blockchain, web-based clients are developed to provide a user-friendly method. These forms are mainly used at On-boarding and Handover phases and enable interoperability with contemporary systems and processes. The former is used for part registration while the latter is used by OEM when the part is received. Additionally, TruCert provides other web interfaces for query the blockchain and display details about parts.

5. Implementation

In this section implementation details of TruCert model are provided in the form of pseudocode representations. An implementation of the TruCert solution is available at.[5]

5.1. Blockchain network creation

In TruCert model a private permissioned blockchain network is used. The network is setup using 4 virtual machines of type *t3.large* on AWS. Each VM has 2 virtual CPUs and 8 GB of RAM. For each VM, a Hyperledger Besu client is installed. VM are configured to allow P2P communication among Hyperledger Besu clients.

5.2. Smart contract development and deployment

Smart contract is a crucial component in TruCert model. It is used for storing details about parts in a secure and transparent manner. Details about parts are stored on blockchain at on-boarding, transit and handover phases by sending transactions calling specific predefined functions. It also provides functions through which network participants can query the blockchain for a specific part. A pseudocode representation of the smart contract code is presented in Algorithm 1 and 2. *Structs* in solidity are used to build relationship between parts and their status updates during the different phases. The main functions provided by the smart contracts are *storePart*: which is called during the on-board phase to register a new part. Prior to this, a check is completed to make sure that

[5] https://bit.ly/3DmFpyy

Table 3
Comparison of *TruCert* and other similar approaches.

	Blockchain	Consensus	Industry	Cost
[37]	Ethereum (Permissioned Consortium)	PoA	Automotive Supply Chain	$0.99–2.078
[38]	Ethereum (Public Test Network)	N/A	Medical Supply Chain	$1.00–4.50
[39]	Hyperledger Fabric	BFT	Drug Supply Chain	N/A
[40]	Ethereum (Azure Managed)	PoA	Cold Supply Chain	N/A
TruCert	Hyperledger Besu (Permissioned Consortium)	PoA	Automotive Supply Chain	$0.56–1.90

the part has not been registered before. *createEvent* is only used during the transit phase. This function is periodically called by the Smart Kit Module to update the status of a particular part. This update include the current GPS location of the part. *handleHandover* which is used when the part reaches its destination. Its necessary to upload an inspection report to describe the conditions of the part in order to complete the handover phase. Additionally, other functions to retrieve information about a specific part, its current status or its full history are provided.

Algorithm 1 On-board Process

Require: $partNo, manufacturer, manufacturingDate$
Require: $supplierID, isCertified, VIN, IPFSFiles$
Require: $truckID, pkitMAC, location, regDate$
  if $partNo \notin RegisterdParts[]$ **then**
    $onboardRecord \leftarrow partInputs$ ▷ Store part record
    $ID \leftarrow 1$
    $Type \leftarrow onboard$
    $Data \leftarrow location$
    $event \leftarrow ID + Type + Data$ ▷ Store part Event
    $ID \leftarrow ID + 1$
  else
    $error \leftarrow Part\ already\ exists.\ Can't\ be\ added.$
  end if

Algorithm 2 HandOver Process

Require: $partNo, deliveryDate, deliveryLocation$
Require: $inspectionReport$
Require: $QADocs$
  if $partNo \in RegisterdParts[]$ **then**
    $handoverRecord \leftarrow partInputs$ ▷ Update Part info
    $ID \leftarrow getNextID()$
    $Type \leftarrow handover$
    $Data \leftarrow deliveryLocation$
    $event \leftarrow ID + Type + Data$ ▷ Store part Event
  else
    $error \leftarrow Part\ is\ not\ registered.\ Can't\ complete\ process.$
  end if

5.3. IPFS network creation

Blockchain network is not suitable for storing large amount of data such as files. As size of data increases, the cost associated with saving it on-chain would increase. For this reason, TruCert uses IPFS for storing documents related to parts. Fig. 7 illustrates use of IPFS within TruCert. This includes CoCs, Quality Assurance documents and Inspection reports. Since these files contain sensitive/private details, a private IPFS network is used. This network is created on AWS using 2 VMs of type *t3.large*. For each document uploaded, IPFS returns a unique hash value which is used as an identifier for retrieving that document. In order to assure the integrity of these files, their hash values are stored on the blockchain by including them as part of transaction payload at both on-board and handover phases. CoC and Quality Assurance documents are used in *storePart* function while inspection report is used in *handleHandover*.

5.4. Oracle development

Blockchain oracle is a service that connects smart contracts with the outside world. Oracles are mainly used for data transmission from the outside world to the smart contracts. Its also used for retrieving data from smart contracts. In TruCert, oracle provides an

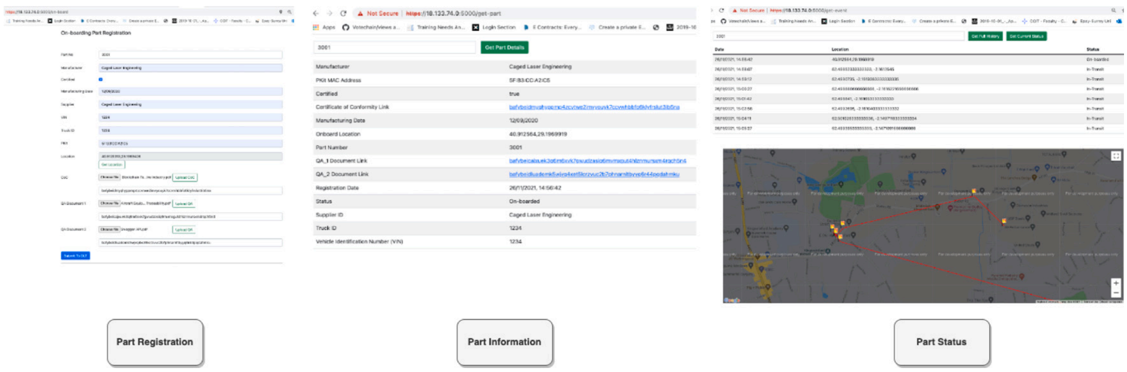

Fig. 8. TruCert sample web interfaces.

easy way through which participants can interact with the smart contract for either storing or retrieving data related to parts. This way, TruCert can be easily integrated with existing systems used by the network participants. A pseudocode representation of the oracle is shown in Algorithm 3. The oracle was developed using Flask[6]; a micro web framework written in Python and deployed on Amazon AWS.

Algorithm 3 Blockchain oracle sample psuedo code.

Require: $partNo, deliveryDate, deliveryLocation$
Require: $inspectionReport$
Require: $QADocs$
Require: $BlockchainNetworkID$
  $gas \leftarrow estimateGas(BlockchainNetworkID)$
  $tx \leftarrow buildTransaction(input, gas)$
  $signed\ tx \leftarrow buildTransaction(tx, privateKey)$
  $tx\ hash \leftarrow send\ RawTransaction(signedTx)$
  if $tx\ hash \neq null$ **then**
    $result \leftarrow transaction\ successfully\ committed$
  else
    $error \leftarrow transaction\ isn't\ successful.$
  end if

5.5. User interfaces

TruCert model has several user interfaces designed in order to facilitate end users to interact with them and add data to the blockchain. An example of such interfaces is presented in Fig. 8. These interfaces are web-based, publicly accessible and compatible with several devices such as desktop and mobiles. The web-based interfaces are used by end users at both on-boarding and handover phases to record details about parts and can also be queried by third parties to analyse details about parts such as the current location of the part and the history of the journey taken by the part. In addition to the end user interfaces, the TruCert solution also has programmable interfaces which can be utilised by third party applications to query part information .

6. Evaluation

In this section, details about *TruCert* model evaluation will be explained.

Table 3 provides a comparison between *TruCert* and other Blockchain-based traceability solutions. The advantages *TruCert* has can be summarised as follows:

- Near real-time data availability: *TruCert* uses IoT devices for providing near real-time data about shipped part through their journey from suppliers to OEM.
- Cost efficiency: the average cost for processing a transaction in *TrueCert* is \$1.23, whereas the average cost is \$1.534 in [37] and \$2.75 in [38].

[6] https://flask.palletsprojects.com/en/2.0.x/

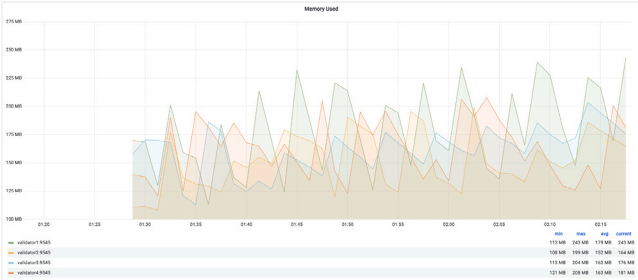

Fig. 9. Blockchain peers memory usage.

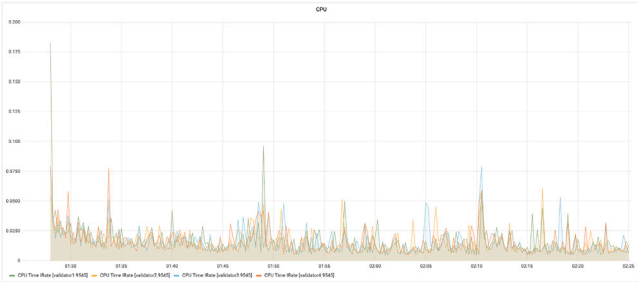

Fig. 10. Blockchain peers CPU usage.

Fig. 11. Block generation time.

- Trusted certification process: Part's certificates such as Quality Assurance and Certificate of Conformity are uploaded prior to shipment which allows OEM to verify the trustworthiness of these certifications in advance.

It worth mentioning that no evaluation is provided in the majority of analysed approaches.

To provide a comprehensive evaluation of *TruCert*, an evaluation approach which consists of four main types has been applied. These types are blockchain network performance, cost analysis, smart contract security, and data integrity.

6.1. Blockchain network performance

The blockchain network was created on Amazon AWS cloud using four virtual machines where a Hyperledger Besu node is running on each machine. These nodes are connected to each other over a peer-to-peer. Figs. 9 and 10 shows the resources in terms of CPU and memory used by each node. The results show that the resources needed to run the blockchain network is acceptable. Further, Fig. 11 shows the time needed by the network to commit a new block to the chain. The average block time was around 6 s.

6.2. Cost analysis

There is a fee associated with submitting a transaction to the blockchain network. A unit of gas holds the unit Gwei and is paid for in Ether. Miners prioritise transactions that hold a higher fee, Thus, the higher the fee is, the most likely that transaction will

Table 4
Cost analysis details.

Transaction	ETHER	US Dollar
On-board	0.000652636	$1.90
Transit	0.00019374	$0.563621
Handover	0.000480398	$1.40

Fig. 12. Slither analysis output.

be included in the next block. Having a cost estimation for developing and deploying a smart contract is important in order to eliminate extra charges which is affected by various factors including loops, arrays, mappings and manipulation.

There are three types of transactions used In TruCert model. For each transaction type an average cost in ETHER and US dollar is presented in Table 4. The cost associated with each transaction cannot be considered low. After investigating the deployed smart contract, it is noticed that loops and arrays are used. This is due to the fact that the deployed smart contract holds business logic for 3 phases within the supply chain, which results in using more arrays and loops to work as expected. It is aimed to modify the smart contract code in order to eliminate or reduce usage of loops and arrays, thus achieving minimal cost.

6.3. *Smart contract security assessment*

Smart contract is different from classical software due to the immutable nature of blockchain. Further, smart contracts are targets to several security attacks as they could hold sensitive data and also being responsible for running the business logic behind the blockchain. Thus, it is crucial to both make sure that smart contracts are tested comprehensively before being deployed and to conduct a security analysis to avoid any possible vulnerability.

In TruCert, a full test is run to make sure that all the functionalities of the deployed smart contract are as expected. This includes running tests to check whether users are authenticated to push data on the ledger and other tests for data integrity. For example, in order to record an event about a particular part during the transit phase, that part should be registered.

For smart contract security analysis, slither was used. Slither[7] is a security tool written in Python for smart contract static and dynamic analysis. Its capable of detecting common issues of smart contracts developed using Solidity language. Slither runs 76 bug detectors to analyse a smart contract such as shadowing, reentrancy, uninitialised variables, multiple constructors, Suicidal and many others. A full list of slither's bug detectors along their details can be found at.[8] The results show that the deployed smart contract has no security issues. The slither analysis output is presented in Fig. 12.

6.4. *Data integrity evaluation*

As parts move through different phases until reaching their destination, maintaining their data integrity is crucial. In blockchain, data integrity can be achieved using cryptographic functions and hashing algorithms. TruCert model maintains data integrity of both parts and their documents.

- Part data integrity: A unique identifier (*partNo*) for each part is used as a reference to any update regarding that part. Creating a new event for a particular part in both *Transit* and *Handover* phases requires that part to be recorded and its *partNo* equals the identifier provided. This type of data integrity is achieved by including controls using (*require*) in smart contract functions. This eliminates any possibility to add any event on blockchain for a part which had not been registered.
- Certification integrity: TruCert model relies on IPFS for storing documents related to parts such as CoCs and Quality Assurance. Once a document is uploaded to IPFS, a unique hash value for that document is retrieved. This hash value is included at the time of registering a part at On-boarding phase. In TruCert model, it is mandatory to upload these documents and include their hash values retrieved from IPFS.

[7] https://github.com/crytic/slither
[8] https://github.com/crytic/slither/wiki/Detector-Documentation

6.5. Limitations

In this work, we proposed *TruCert* as a generic solution for achieving product traceability in supply chains. The results of the experiments conducted to validate the approach's feasibility show that it operates effectively to achieve end-to-end visibility for complex supply chains. However, our approach faces the following challenges that we plan to address in future work. The first challenge concerns the performance of Blockchain network during transit phase. The experiments' results showed that the deployed blockchain network can handle transactions submitted periodically by Tkit modules attached to each truck data in a reasonable and acceptable time. However, we envision that transaction processing time will increase when the number of the Tkit modules increases which result more transactions submitted at the same time, or the time period in which Tkits submit transactions decreases.

The second challenge concerns the security and data accuracy of Tkit modules. Tkit modules play a critical role in providing near real-time insights about shipped parts. These modules are limited in terms of computational resources which makes them vulnerable to several attacks. This would result in submitting incorrect information about parts. Another challenge facing our proposal is connectivity at truck level. Having a reliable internet connectivity is mandatory in order for Tkit modules to periodically submit collected data about part to Blockchain. This issue will limit the functionality of our solution when trucks travel through rural areas or cross different countries.

7. Threats to validity

In order to evaluate the effectiveness of the TruCert solution, a local blockchain testbed is developed to assess this solution with respect to scalability, usability, transaction cost, and security. However, it is acknowledged that the following threats to validity of this evaluation exist.

- **Location of blockchain nodes** Our evaluation included network performance to assess the TruCert's efficiency to commit new blocks to the blockchain. Our current setup is hosted on AWS cloud and relies on its default algorithms to host different blockchain nodes on different virtual machines. As such, the network performance can be affected by the location of these nodes and therefore the results reported here are dependant on this factor.
- **Capability of the blockchain nodes** The blockchain nodes used within our testbed were AWS standard t3.large. The results reported for CPU and memory consumption rely on the standard configuration of these instances and can vary for nodes with different specifications.
- **Choice of blockchain** Within our testbed, Hyperledger Besu is used to set up a network of permissioned blockchain utilising Proof of Stake consensus algorithm. Further, IPFS is used to facilitate decentralised storage of product certificates and associated documents. These factors influence the evaluation outcomes reported with respect to block size, block generation rate, and scalability of the TruCert solution.
- **Transaction cost** In order to ascertain the financial efficiency of TruCert solution, our evaluation included identifying the cost of executing smart contracts in US Dollar ($). As the cryptocurrency is volatile, this measurement can change and the figures reported are for the dates when our experiments were conducted.
- **Validity of part information** TruCert model relies on part-specific information such as Part No and description to develop an immutable chain of records for each part including the CoC and other quality assurance documents. Therefore, the integrity of information stored in the blockchain relies on accuracy of data fed into the system.

8. Conclusion

Automotive supply chains have complex structure as they consist of several entities (suppliers and suppliers of suppliers etc.) which are geographically distributed. This complexity introduces implications with respect to transparency in operations, traceability of components across production plan of Original Equipment Manufacturer (OEM)'s suppliers within the supply chain network, and visibility for tracking & tracing of components, parts and/or finished products. In this paper, TruCert is presented to address the challenge of product certification by tracking and tracing parts across a autonomous automotive supply chain. TruCert is a blockchain-based solution that enables product certification through traceability of parts in automotive supply chains in a decentralised, secure, trusted, transparent, and reliable manner. Detailed description of the TruCert solution is presented including its architecture and data model as well as detailed implementation such as consortium blockchain testbed, smart contracts, and oracles which showcase the contribution to the scientific community. The outcomes of evaluation indicate the efficiency of TruCert solution with respect to security, cost, and performance and therefore demonstrate its effectiveness to achieve end-to-end visibility for complex supply chains in general and autonomous automotive supply chains in particular. Additionally, this work introduces opportunities to for providing visibility into a vehicle's lifecycle which can be used to aid in-depth diagnostics and predictive maintenance. However, such research directions will require deeper analysis of performance implications of blockchain-based solutions (such as TruCert) including scalability and energy consumption as well as the financial cost of transactions which will affect the feasibility of such solution.

CRediT authorship contribution statement

Mohammed Alsadi: Writing – original draft, Investigation. **Junaid Arshad:** Conceptualization, Methodology, Writing – original draft. **Jahid Ali:** Conceptualization, Methodology, Investigation. **Alousseynou Prince:** Writing – reviewing, Methodology, Investigation. **Shishank Shishank:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request

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