https://doi.org/10.1016/j.eswa.2021.115101

A Blockchain-Based System to Enhance Aircraft Parts Traceability and Trackability for Inventory Management

George To Sum Ho[1], Yuk Ming Tang[2,*], Kelvin Kun Yat Tsang[3], Valerie Tang[4], Ka Ying Chau[5]

[1]Department of Supply Chain and Information Management, The Hang Seng University of Hong Kong, Shatin, N.T., Hong Kong; Email: georgeho@hsu.edu.hk

[2,*]Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong; Email: mfymtang@polyu.edu.hk

[3]Department of Supply Chain and Information Management, The Hang Seng University of Hong Kong, Shatin, N.T., Hong Kong; Email: kun-yat.tsang@connect.polyu.hk

[4]Department of Supply Chain and Information Management, The Hang Seng University of Hong Kong, Shatin, N.T., Hong Kong; Email: valerietang@hsu.edu.hk

[5]Faculty of Business, City University of Macau, Macau; Email: gavinchau@cityu.mo

ABSTRACT

Aircraft spare parts inventory management (ASPM) has played a critical role in tracing and tracking spare parts as any related maintenance or movement shall be recorded. Traceability and trackability of data ensure the compliance of airworthiness requirements. The International Air Transport Association (IATA) has strongly emphasised the significance of quality traceability data throughout the aircraft part's life cycle, leading to enhanced inventory control accuracy, reduced maintenance error, and effective decision-making processes. However, with the rapid increase of spare parts types, the complexity of aircraft parts multi-stage supply chains leads to inefficient tracing and tracking operations with unsatisfactory traceability data quality and information security. This paper proposed a blockchain-based system that provided a managerial platform for accurate recording of spare parts traceability data with organisational consensus and validation using Hyperledger Fabric and Hyperledger Composer. A data model has been determined based on the existing ASPM, enabling information integrity during transaction operations. The channel mechanism has yielded a trustful data sharing platform between each contracting organisation for logistics and operational arrangements, which has enhanced information visibility and security. The blockchain-based system, executed under a decentralised ledger mechanism, shall improve the quality of traceability data and reliable information sharing within the spare parts supply chain. The enhanced blockchain-based inventory management system can establish the digital twin of aviation as part of Industry 4.0 in the future.

Keywords:

Blockchain, Hyperledger, Aviation, Aircraft Spare Parts, Inventory Management, Digital Twin, Traceability, Trackability

1. Introduction

As defined by International Civil Aviation Organization (ICAO), the term *airworthy* refers to the status of an aircraft, engine, propeller, or part when it conforms to its approved design and is in a condition for safe operation (Coutu & Alblowi, 2014). To promote and achieve the international standardisation of airworthiness, ICAO has issued the standards and recommended practices that contracting states are obliged to implement in their national legislations (ICAO, 2015). With the existence of airworthiness legislation, an aircraft should be safely reliable and complete its maintenance process before its release to services. Hence, airlines have the full responsibility to ensure their fleets have conducted the required maintenance based on the approved maintenance programme. The maintenance programme has further determined which aircraft parts shall be inspected, replaced, and maintained within the planned schedule based on the reliability data such as the recommended time interval of failure detection from the original equipment manufacturer (OEM; Mostafa et al., 2015).

Aircraft spare parts inventory management (ASPM), a critical operation in the maintenance, repair, and overhaul (MRO) organisation, is meant to manage sufficient spare parts supplies for maintenance services and prevent spare-parts-related flight cancellations and aircraft-on-ground (AOG) situations (Keivanpour & Kadi, 2019). It has been the key to success for MRO organisations and airlines in terms of optimum MRO efficiency throughout decades of air transportation service. Aircraft parts can be classified into various types (i.e., repairable, expendable, and recoverable), with each type having a typical ASPM process based on the design criteria by the OEM. Activities such as servable components exchange, loan services, and record-keeping have ensured the availability of spare parts at the lowest cost and enable the shortest times for aircraft maintenance with airworthiness provisions (Zheng et al., 2019).

One of the significant characteristics of ASPM is tracing and tracking aircraft parts, both inter-organisational and externally, across the supply chain (Ngai et al., 2014). *Tracing* involves determining the historical status of the aircraft parts based on the traceability data, and *tracking* refers to the resolution of the current condition. Traceability data of aircraft parts includes data related to maintenance, modification, ownership change, and movement history should be detailly recorded throughout the parts life cycle. Traceability data will be shared with participants within the supply chain, reducing information asymmetry and enhancing supply chain agility (Resende-Filho & Hurley, 2012). High quality of traceability data transmitted will advance spare parts tracing and tracking performance with enormous benefits to all organisations, for example, improving inventory control accuracy, reducing maintenance error, and making decision-making processes and maintenance planning more effective (IATA, 2015). However, the number of aircraft types and unique parts has significantly increased in recent years, and the spare parts supply chain has become more complex (IATA, 2015). Tracing and tracking activities through the existing Enterprise Resource Planning (ERP) system are time-consuming and unlikely to produce accurate traceability data for sharing between organisations. Researchers have proposed employing the Internet of Things (IoT) with radio-frequency identification (RFID) tags to simplify existing part tracing and tracking processes and increase efficiency throughout the supply chain (Sahay, 2012; Chan et al., 2020). However, the problems and issues, including airworthiness document tracking, information security, and access rights, have not entirely been resolved. The lack of an appropriate data management solution will continuously affect maintenance services planning, efficiency, and quality. Aircraft maintenance services may be delayed due to inadequate ASPM; hence airlines will lose money every minute without fleet availability, overall affecting the development of global aviation operations.

There have been intensive discussions in proposing blockchain applications in business management in recent years, especially in supply chain management. Researchers have determined the effectiveness of achieving transparency and visibility of data sharing between supply chain participants using blockchain (Korpela et al., 2017). Other research has also shown that the successful integration of blockchain and IoT can enable reliable and accurate data collection for perishable logistics traceability (Jun et al., 2018). The blockchain is intended to be synchronised and distributed across peer-to-peer networks, which enable data sharing and multi-organisation business coordination, as in a supply chain network. The computational agreements declared by relevant parties and stored in the blockchain system are known as *smart contracts* (Alharby & van Moorsel, 2017). The smart contract, an extension of blockchain, is a digital protocol that verifies, facilitates, and enforces the agreed contract terms without requiring mediator interventions and enhances credibility between transactions. It also keeps potentially fraudulent and inaccurate transactions outside the system to ensure proper administration of the agreement. The executed codes that power the smart contract have pre-set obligations and rights to control certain assets within the shared ledger. The decentralised blockchain network executes the transactions among the parties within the contract agreement automatically and acts as a third party in the verification process. Apart from physical sensor technologies, such as QR codes and RFID, the biological features or the product's material composition signatures are very useful for product counterfeiting in the supply chain (Leng et al., 2019a).

A number of reviews have discussed the incorporation of blockchain technology to enhance the security, transparency, and traceability of data in the supply chain. Leng et al. (2020a) performed a detailed survey on blockchain-powered sustainable manufacturing in Industry 4.0. The study investigated the framework and process of implementing the blockchain network in the manufacturing industry. It reviewed many pieces of literature in developing transparency and traceability of data for the sustainable development of Industry 4.0. Leng et al. (2020b) discussed a new generation of secure information technology using blockchain technology for enhancing security in smart manufacturing and its future research directions.

Currently, the research in blockchain-related implementations in ASPM is still nascent; this paper is aimed to improve the lack of knowledge in this area and considers whether blockchain is an effective approach to resolving challenges related to traceability data quality. It is feasible to believe that blockchain, with the capability of processing transactions with consensus under decentralised ledgers and hashing both tangible and intangible assets, can achieve secured and transparent aircraft part provenance data throughout the life cycle. Under the blockchain-based environment, organisations that participate in the ASPM process can acquire reliable, secured, immutable aircraft parts data through the decentralised ledger technology (DLT) of the blockchain network. The reduction of information asymmetry shall enhance traceability data accuracy and create trustful relationships in data sharing between contracting organisations. Based on the existing ASPM process, the permissioned blockchain has been considered the most suitable to implement. The permissioned blockchain type can maintain a private ledger among the participating peer nodes using the channel communication mechanism. Hyperledger Fabric and Hyperledger Composer are open-source tools for designing the basic system framework of the permissioned blockchain. Hyperledger Fabric, with pluggable consensus protocols and a membership service node mechanism, enables the modular construction of a peer-to-peer network with private communication channels. Hyperledger Composer can model the ASPM business network definitions and support the Hyperledger Fabric runtime and infrastructure.

Although some research implemented the blockchain network in a variety of applications, including manufacturing, healthcare and Industry 4.0, most research is based on conducting survey studies and proposing theoretical frameworks for the application domain. Research on using the blockchain network for aircraft inventory management is still in the initial stage. In particular, not much research has practically applied the private or public blockchain into its domain applications. This article aims to address the key research question on practically implementing the ASPM through the Hyperledger Fabric Private Chaincode to enhance traceability and trackability for inventory management. Further, we present the following key contributions in this study: (a) To the author's knowledge, this is the first attempt to develop the Hyperledger Fabric network based on the ASPM scenario; (b) we proposed and developed the blockchain-based system framework to enhance the quality of aircraft parts traceability data under the mechanisms of Hyperledger Fabric—the system was tested through implementation and sensitivity analysis; and (c) we designed and formulated the communication channels within the Hyperledger Fabric Private Chaincode. The peer-to-peer Hyperledger Fabric network is designed to connect all organisations within the spare parts supply chain and enhance efficiency during parts transactions and information exchange security in a distributed-ledger manner.

The remainder of this paper is organised as follows. In the next section, we review the related literature of existing ASPM development. Next, the design architecture of the proposed blockchain-based system is described with system sensitivity analysis, followed by a discussion of the sensitivity analysis and the implementation of the blockchain-based system. The limitations of the current research and future research directions are given in the conclusion.

1. Literature Review

This section is dedicated to illustrating the recent development of ASPM in the aviation industry and the capability of blockchain implementation to the improvement of parts traceability based on the existing literature.

2.1. Aircraft Spare Parts Management

In 2015, IATA performed an aviation business review and declared that component maintenance costs are around 24% of airlines' direct maintenance costs per flight hour (IATA, 2015). After examination, it encouraged implementing digital platforms to improve security and safety of a business, particularly in the documentation of aircraft parts history and overhaul activities. MRO documentation is still conducted manually and on paper, and incomplete history documentation makes a vast amount of financial loss typical due to the high cost of parts. Hensel (2017) posited that digital documentation such as paperwork synchronisation and record computing systems would reduce potential errors and delays and intensify the overall documentation cycle.

The demand and inventory level of aircraft spare parts directly depends on the reliability of the part type. The ASPM has continuously estimated the residual lifetimes of spare parts, based on design and reliability data from the OEM and historical data of the spare parts through tracing and tracking activities. Yongquan et al. (2016) proposed a new prediction method for forecasting the failure time and failure number of new aircraft parts with limited historical operation data. This method considered that the demand for spare parts could be affected by fleet size and the length of the prediction interval, so that OEM and airlines can adjust the decision of quantity and ordering time. The study also indicates that the accuracy of demand prediction depends on incorporating the historical data of the aircraft parts. Lin et al. (2017) proposed a maintenance decision-making support system for minimising maintenance costs and maximising fleet availability. The proposed approach simplifies equipment management by integrating data acquisition and processing. Both studies specified that the required traceability data from multiple sources could enable the development of precise reliability information system for aircraft parts.

The performance of ASPM greatly depends on the quality of traceability data shared from the contracting organisations in the supply chain. High-quality data sets enable cost-effective, focused, and rapid aircraft parts tracking throughout the life cycle and demonstrate compliance with airworthiness requirements. Studies have proposed the suitability of RFID technology for asset tracking and tracking and resource management in the supply chain industry (Fescioglu-Unver et al., 2015; Lazarevic et al., 2011; Wang, 2014; Choi, 2015; Holmströ, 2009; Saygin & Tamma, 2012). Chang et al. (2006) presented an RFID-enabled system integrating an aircraft scheduling system and an aircraft parts inventory control system to enhance safety and on-time performance. Ng et al. (2006) raised replacing traditional paper-based work-in-progress information with rewritable RFID tags to improve the information accuracy of ongoing MRO activities. Ramudhina et al. (2008) introduced the generic framework to support the selection of RFID-based control systems with application to MRO activities of an aircraft engine manufacturer. Two RFID-based tracking systems are also proposed that can be applied based on existing technology and new developing technologies such as decentralised processing and wireless communication. Yang et al. (2018) expanded the use of ultra-high frequency RFID tags on the aircraft landing gear for health monitoring, suggesting reduced maintenance and operational costs and extended service life of landing gear.

However, there have been increasing investigations of concerns related to security and privacy when applying RFID in the supply chain and product life cycle management process. Lazarevic et al. (2011) commented that the owner of the product item might not necessarily have an awareness and knowledge of the presence of an RFID tag, which may collect sensitive data without consent. The security and privacy issues demanded a need for RFID users to be made aware that the information should be kept secure through manageable means. Fescioglu-Unver et al. (2015) further illustrated that RFID systems have the potential for unauthorised access by attackers. Security attackers may interfere with the RFID tag reader and send fraudulent messages to tags and readers. Privacy attackers can collect sensitive information from the tags without identification and authentication through special attack algorithms. All potential threads will lead to questioning the reliability of traceability data, especially in sharing data with other organisations.

2.2. Blockchain Technology

Blockchain is a distributed transactional data structure that stores records and other information managed by the consensus mechanism and secured by cryptography. *Distributed ledger technology* (DLT) forms the basic design framework for many blockchain-based systems (Masood & Faridi, 2018). In a blockchain system, data records are called *blocks*, and distributed ledgers are called *chains*. Various blocks and chains are connected to create a blockchain computer network, and the ledger transactions are processed and verified by the cryptography autonomously (Zhai et al., 2019). A completed blockchain system can be classified as public (i.e., *permissionless*) or private (i.e., *permissioned*; Falazi et al., 2019). The difference between the two is the nature of membership, in which the authorisation is required for participating in the blockchain network. A *public blockchain* means anyone can register and take part in a system without permission. The consensus mechanism also provides an algorithm for validating transactions, securing, and trouble-shooting the peer-to-peer network operations base on the agreed rules (Nakamoto, 2008). Bitcoin, the first public blockchain system, adopted the *proof of work* (PoW) consensus mechanism, which is a protocol for proving verification under a particular computational effort within a time interval by forcing computers to compute (Dominique & Sothearath, 2019). Research has claimed that PoW enhances blockchain security and assures that transactions are processed promptly, which is beneficial for public blockchains due to the high number of participants. Even though PoW requires substantial electricity to power the computations, which is the costliest mechanism to reach consensus globally, it serves as the most fundamental consensus mechanism in later blockchain developments.

A key benefit of using the distributed system is that no single entry controls the operation, which solves the problem of accountability and disclosure between individuals and parties. Crucial data in the blockchain can be updated in real time, eliminating the labour and error of individual internal data reconciliation and providing each participant with high visibility of the actions arising inside the network. The value exchange can be verified and completed safer, faster, and cheaper compared to traditional third-party communication. The blockchain data is *immutable*, which means the recorded transactions cannot be altered or deleted retroactively. Nawari and Shriraam (2019) also mentioned that this feature provides a data provenance that identifies the data history of time and location throughout the lifetime. The data security and encryption of blockchain have improved trust, efficiency, and transparency in the information sharing between businesses, which is a great advantage for digital supply chain management.

Recent studies have discussed the implementation of blockchain technology in aviation operations. Wang and Li (2019) discussed the technical construction of a supply chain traceability model for aircraft parts integrated with the IoT. The study also reviews the current traceability process and information involved in ASPM. Aleshi et al. (2019) proposed a secure blockchain system in storing aircraft service records in a digital distributed ledger. The data and transaction structures are designed based on the Federal Aviation Administration (FAA) requirements of maintenance record logbooks. The stored information is suggested to be trusted with consensus based on the Proof of Elapsed Time (PoET) algorithm of Hyperldger Sawtooth. Wickboldt and Kliewer (2019) presented a blockchain-based IT artefact that enables the digitisation of the documentation process within the ASPM based on Hyperledger Fabric. The system is characterised by multiple stakeholders, multiple types of certificates, and decentralised authorities.

The literature in applying blockchain in aviation that can be analysed is limited since the blockchain concept is new to aviation. Santonino III et al. (2018) agreed that applying the blockchain system to solve the aircraft parts inventory problem is essential and can significantly impact future operational developments in aviation engineering companies. Lufthansa Industry Solution and Air France KLM have started similar research and experiments with the technology and currently discussing the possibility of the implementation of maintenance workflows and processes (Aleshi et al., 2019). According to Technavio (2018), blockchain can be applied in MRO logistics. Due to the rapid growth of the MRO logistics market, the number of logistics activities is increasing dramatically. Logistics companies should implement more efficient ways to deal with the cases; otherwise, they might not be able to afford large amounts of MRO logistics activities. Therefore, new technology should be applied to enhance the process and increase efficiency. Hence, blockchain technology, which can ensure the security of transaction records and distribute the required information to other stakeholders, can be used in the market. Logistics companies can have a central authority to maintain records, enhance traceability of logistics records, and improve the security of data (Helo & Hao, 2019).

Since every peer in an asset's life cycle, including manufacturers, maintainers, and airlines, has different record systems for asset management, the traceability of assets and consistency of asset status cannot be ensured. Bas de Vos (2017) suggested using blockchain technology for asset management, so every peer can add blocks to the asset records. Therefore, a trust-worthy asset management system can be built with real-time status and traceable records. Every peer with access permission can view the records and edit the state of assets but will not be able to write without having the previous records. As blockchain technology can provide private and secure records and apply smart contracts in every transaction, it can be widely involved in aviation activities, especially those with transactions between different parties when traceability of records needs to be ensured. Therefore, the implementations mentioned above can help to enhance transaction processes and maintain the security of data, which is the greatest concern in aviation activities.

3. Blockchain-Based System Architecture

Recall that the aim of this paper is to present a blockchain-based system to resolve the challenges related to traceability data quality for aircraft spare parts. In this section, the scenario of aircraft parts management is given first to bring in all organisational parties involved in the aircraft parts management, which are the OEM, MRO organisation, airline, and the logistic service provider, and to introduce their characteristics. the traceability information set of the blockchain-based system is formulated to provide essential information that leads to better parts management, quality assurance, information visibility, and authentication. Then, the analysis of the operational process and the organisational relationships that lead to the design of the blockchain-based system is given. Lastly, the concept of formulating the blockchain network with multiple digital twins in aviation is proposed.

3.1. The Scenario of Aircraft Parts Management

Fig. 1 shows a typical process to implant aircraft parts operations and collaboration between the organisational parties, which include the OEM, MRO, airline, and logistic service providers. Also, it demonstrates the general implementation of a blockchain-based system in the spare parts supply chain.

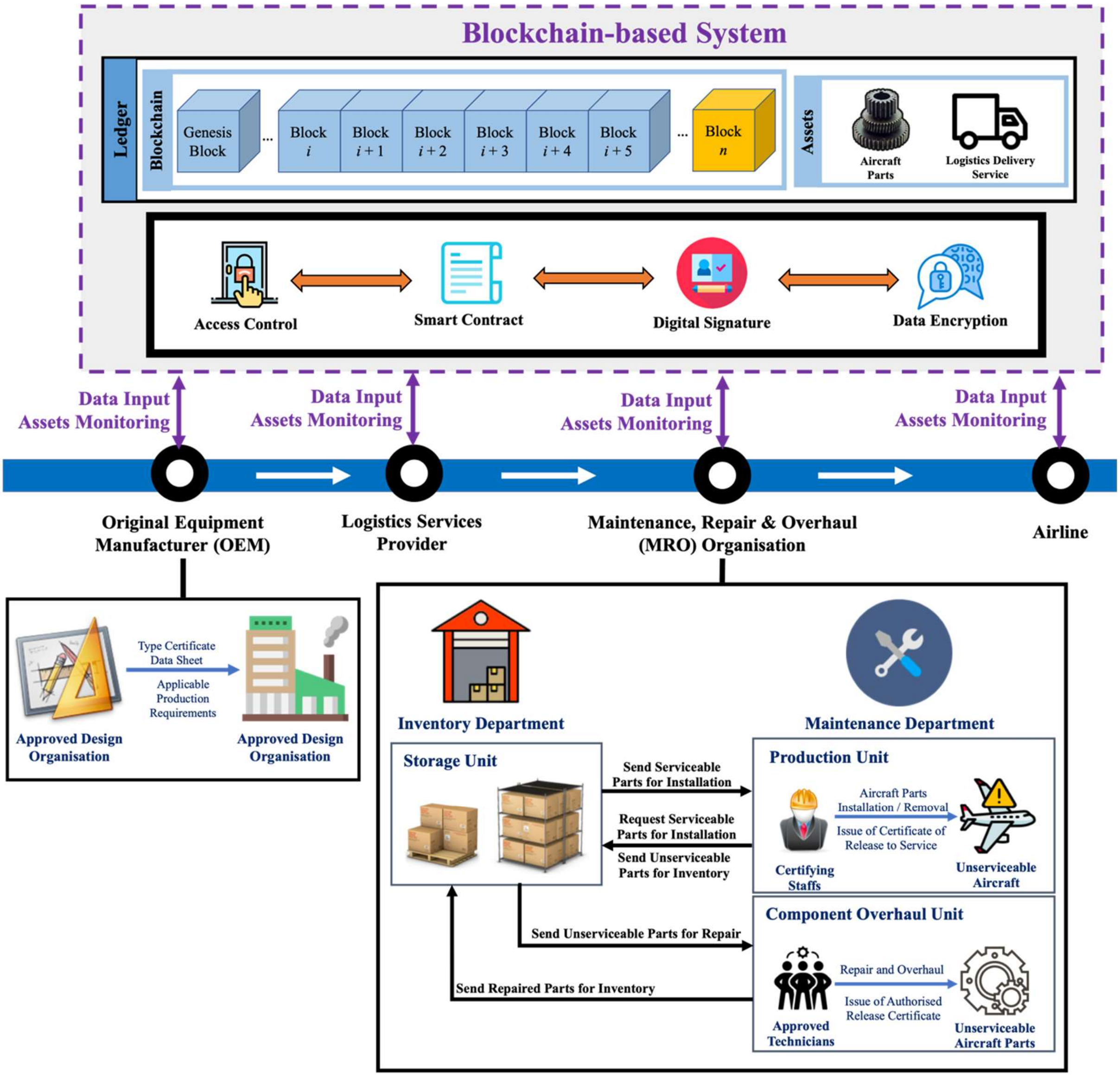


Fig. 1. Aircraft Spare Parts Operational Process with Blockchain-based System.

OEMs are the aircraft and parts manufacturing companies that responsible for designing, building, testing, and maintaining aircraft parts. OEMs should always have the complete concept of each aircraft type with all the primary data of the aircraft type, including the design of the aircraft and the raw data for each part. It can signal amendments to the maintenance program depending on reliability data shared by the MRO organisations and airlines. OEMs release maintenance planning documents for airlines to construct maintenance schedules for their fleets and maintenance manuals for MRO organisations to conduct maintenance work. Being an approved production organisation, certifying staff from an OEM may issue an authorised release certificate that the produced aircraft parts were manufactured with approved or non-approved design date. This can ensure the part is in safe condition before sending it for installation.

The *logistics service provider* is responsible for delivering the ordered aircraft parts to the various MRO originations. Providing data on the real-time location and shipment details of the delivery, the logistics company will share the delivery status with all other organisations for effective time management.

The *MRO organisation* is responsible for repairing any category of mechanical or electrical problems in an aircraft while it is out of order, as well as performing routine checks to prevent future problems. The MRO organisation's maintenance department has two major units: production and component overhaul. The *production unit* is responsible for the installation and removal of parts when certified staff issue a certificate of release to service. Moreover, the production unit may request serviceable parts from the inventory department for maintenance services. The *component overhaul unit* is in charge of conducting repairs and overhaul work on damaged parts when an approved technician issues an authorised release certificate. The repaired parts shall be sent back for storage. The critical operational issue for aircraft part inventory management has played an essential role in MRO activities. Effective inventory management can enhance the efficiency of maintenance work to avoid an aircraft-on-ground situation, which affects the airline's business. The inventory department shall always order spare parts from the OEM and prepare the stored and serviceable parts for both emergencies and planned maintenance at the same time. Subsequently, all parties within the MRO organisation should follow the maintenance standards and instructions published in the OEM documents and report the updated aircraft status to the customer airlines.

Airlines provide air transport service for travelling passengers and have the responsibility to ensure the continuing airworthiness of their aircraft fleets and parts. Certifying staffs assigned by airlines are accountable for conducting the necessary maintenance daily checks between each flight. For any discovery of fatigue or broken parts, critical aircraft spare parts are required for replacement; otherwise, the aircraft should not fly due to the invalid certificate of airworthiness. The technical logbook, which contains the history of aircraft maintenance and other activities, should be kept safe on board. Also, airline staff should always monitor and communicate with certifying staff to ensure the maintenance progress is on track, to avoid an aircraft-on-ground situation and any flight delays or cancellations, to maintain the airline's business reputation. For any maintenance activities related to base maintenance, the airline should inform the OEM of the necessary parts and request a suitable environment and qualified staff for maintenance checks from MRO organisation production units.

The proposed blockchain-based system with the feature of decentralised distributed ledger technology shall enhance the information transparency and security of aircraft spare parts management in the aviation industry. The operation implementation scenario presented here illustrates that the organisation participant can manage, input data, and monitor each stage and activity in aircraft parts management. The assets of the proposed blockchain network are aircraft parts, logistics delivery services in which data is managed under the blockchain, and encryption mechanisms. The data of these assets serve as the primary information required by related organisations for daily transactions, reliable interactions, and continuous asset monitoring. For example, the inventory department of the MRO organisation shall input the essential data for parts storage, such as the part number, serial number, location, and certification status with the certificate copy attached. The inventory department may monitor the delivery status of newly ordered spare parts from the logistics services provider, the repair status from the component overhaul unit, and even the historical data of the particular parts from its manufacturing to remove from services through the blockchain-based system. Permissions for sharing and accessing information are defined by the access control policy in the smart contract logic and digital signature protocol to maintain data security and integrity.

3.2. Information Set of the Blockchain-Based System

The analysis of the studies in the previous section has indicated the importance of implementing traceability in aircraft spare parts management, which leads to better parts management, quality assurance, information visibility, and authentication. The decision of the information set applied in developing smart contracts has an essential impact on organisational communication, both in efficiency and effectiveness in the blockchain system. The initial step of designing an adequate traceability system is to summarise the key factors that influence the operation and supply chain for preparing aircraft parts for maintenance and continuous monitoring.

For various types of information at each stage of aircraft parts manufacturing, modification, installation, repairing, the inventory shall always be recorded to achieve the optimum level of traceability. Although the aviation industry has already had explicit instruction in recording information based on local airworthiness requirements, the traceability of parts has always been problematic when involving a large amount of data processes and various organisational practices. As the blockchain requires a standard information set format when executing transactions between organisations, the comprehensive traceability information sets for recording and sharing have been prepared in Table 1 for better communication, especially concerning aircraft parts quality and current status. Parts information includes the part number, serial number, description, dates on and off the wing, and detailed specifications related to the life cycle. The name of the airline shall indicate the responsible end-user. The installed aircraft and assembly information includes the details of aircraft installations and products assembled. The process and quality information contains all process data involved in the manufacturing, quality activities, storage of the aircraft parts. The supporting documents shall be associated with necessary certificate copies for reference. Finally, the handover shall indicate the latest organisation to which it was delivered or handed over. The traceability information listed only serves as the recommended data set in preparing the transactional logic for the best practice of traceability based on the existing aircraft parts operation. The final provision of essential and non-essential traceability information shall be determined by the business preferences and agreements between organisations.

Table 1
Traceability Information Set

Information Sets	Sub-Category	Description
Parts Information	P/N	Part Number which is the standard identity for the subject part, assembly, kit or material item
	S/N	Part Serial Number with a code identifying the party assigned it, will uniquely identify the part through its life, whether or not the Part Number changes
	Part Description	The full description name of a part or component according to the manufacturers souring document
	Date on Wing	Part installation date
	Date off Wing	Part removal date
	TSN	Time Since New to be reported in flight hours
	CSN	Cycles Since New to be reported in flight cycles
	Life Limit Hours	Specified in the type design, the mandatory continuing airworthiness information or instructions for continuing airworthiness
	Life Limit Cycles	Specified in the type design, the mandatory continuing airworthiness information or instructions for continuing airworthiness
	Hours Remaining	Report hours
	Cycles Remaining	Report cycles
Operator		Name of the airline
Installed Aircraft	Type and Model	Aircraft type and model on which the part is installed
	AC REG	Aircraft registration
	MSN	Manufacturer's Serial Number assigned by manufacturer to designate aircraft
	MTOW	Maximum Take-off Weight as limited by aircraft strength and airworthiness requirements (For landing gear part)
Installed Assembly*	Date on wing	Assembly installation date
	Date off wing	Assembly removal date
	Type	Assembly type as designated by the manufacturer
	S/N	Assembly serial number
	TSN	Time Since New to be reported in flight hours
	CSN	Cycles Since New to be reported in flight cycles
	Thrust Rating (lbs)	For engine part only
Process Information	Process Names/Details	Information and details about all process involved throughout the lifecycle
	Location	Location of the process occur throughout the lifecycle
	Timestamp	Timestamp of the process occur throughout the lifecycle
Quality Information	Audit Reports	Audit-quality reports done throughout the lifecycle
	Test procedures and reports	Test procedures and reports done throughout the lifecycle
	Quality Certification Data	Quality certification data of the part
Supporting Document	Reason for a Record Entry	Reason such as production, installation, removal, change of operator, change in operational parameters, repair
	Reference	Name of approval document
Handover		Name of the responsible organisation

*Assembly refers to an engine, an auxiliary power unit (APU), a landing gear and the like

3.3. Blockchain-Based System Architecture

The blockchain has enabled enhanced information transparency and security through decentralised distributed technology. Based on the mechanism of Hyperledger Fabric and current operations in aircraft spare parts management, a complete blockchain-based aircraft parts system architecture is presented in Fig. 2 to enable organisations in the aviation industry to manage and update any activities related to certification, maintenance, and the supply chain. The participants, called the *system users*, are the OEM, logistics services provider, and departments of an MRO organisation. The airline shall be equipped with a front-end client application to communicate and perform transaction of aircraft parts in the Hyperledger Fabric network. The transaction shall act under the chaincode associated with consensus and validation mechanisms that enable successful and consistent execution. The modular architecture of the proposed system is supported by a flexible design providing high levels of privacy, resiliency, flexibility, and scalability. Its versatile and modular design can satisfy most industry use cases, including aviation, and enable scalability while preserving privacy most straightforwardly.

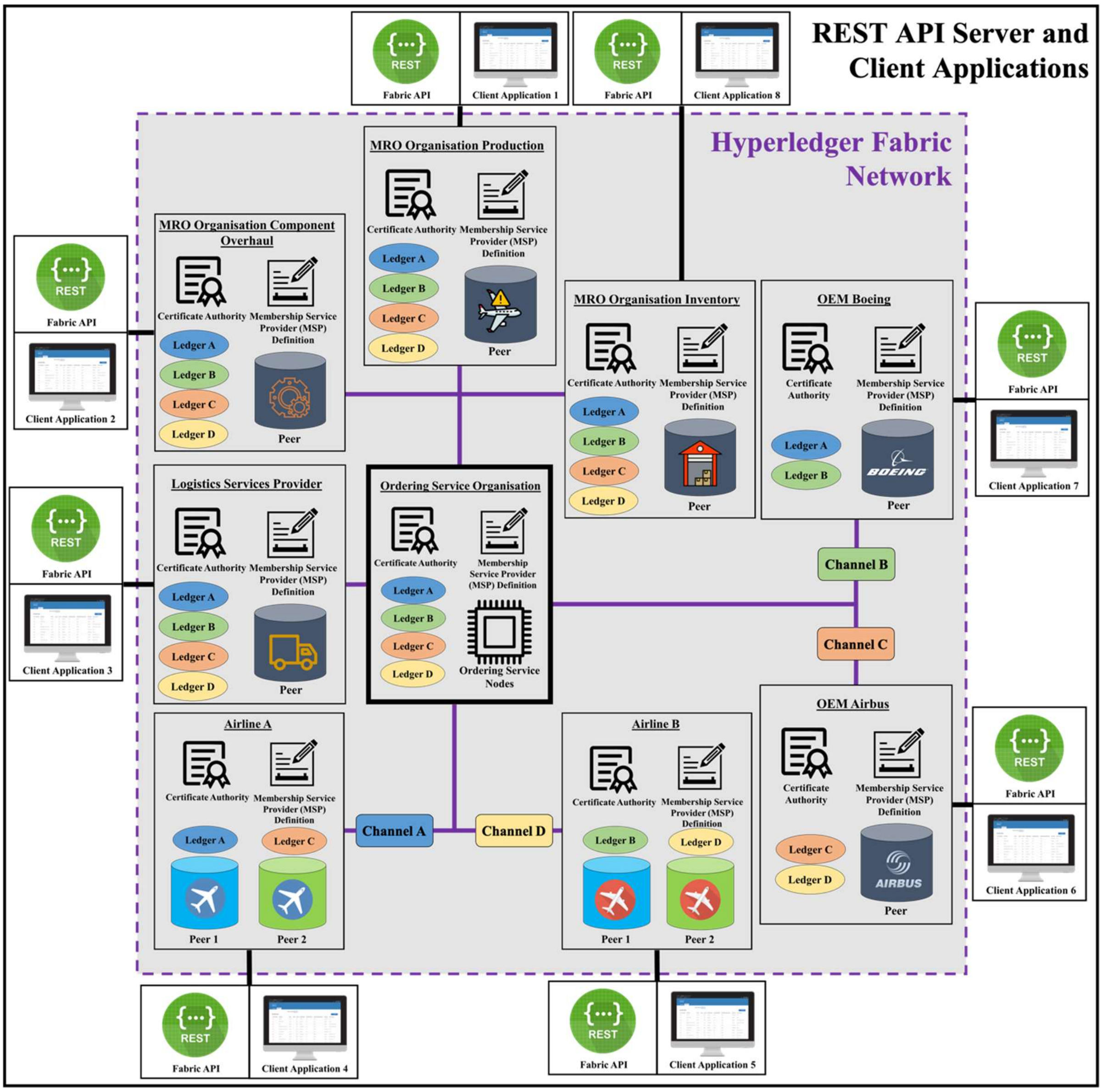


Fig. 2. Blockchain-Based System Architecture for ASPM.

The proposed Hyperledger Fabric network is composed of one to two peer nodes for each organisation, which host instances of chaincodes and ledgers for encapsulated and immutable recording, depending on the nature of the business operation. Peers, such as OEM Boeing, can keep more than one ledger to communicate with various peers with different channels. And peers within the same channel shall agree to cooperate by sharing and managing identical copies of the ledger related to that channel. Since the peer serves as the host of chaincodes and ledgers, client applications shall be connected to the peer using the Fabric Software Development Kit (SDK) for accessing resources, such as transactions and query ledgers. For example, Client Application 7 has connected to peer OEM Boeing to invoke chaincode for a transaction proposal and ledger update.

The ordering service organisations within the Hyperledger Fabric network demonstrate the feature of deterministic consensus algorithms, which are mainly processed by the ordering node. It processes the transaction orders based on the endorsement of chaincode execution, which improves Fabric scalability and performance. The ordering service recognises authorised transactions, turns them into a block, and sends the blocks to the executing peers. The network divides the stakeholders into different channels and creates a decentralised organisation structure that enables a permissioned blockchain-based system under a partially decentralised self-organisation. This mechanism can offload and optimise system performance (Leng et al. 2020c).

To get into the channel to do the transactions, every participating organisation must have a *managed service provider* (MSP) identity. An MSP is a set of files that allow organisation added to the configuration of the network that is used to explain an organisation both privately and externally. That means there is an approver for the organisation to decide who its admins are and to allow the organisation to do their transactions. While *certificate authorities* create the licenses that stand for identities, the MSP holds a file of permissioned identities, which means that if an organisation wishes to join the channel, the organisation's members would need to be included in the channel configuration by the MSP. Furthermore, local MSPs are represented as a folder structure on the file system; channel MSPs are described in a *channel configuration*.

Channels are set based on organisational business needs regarding information sharing security. Some organisations would not like to disclose confidential information and data to the competitors. Thus, organisations can build channels within the blockchain network to communicate privately. The list of channels is shown in Table 2.

Table 2

List of Channels

Channel	Organisations
A	OEM Boeing Logistics Services Provider MRO Organisation Inventory MRO Organisation Component Overhaul MRO Organisation Production Airline A
B	OEM Boeing Logistics Services Provider MRO Organisation Inventory MRO Organisation Component Overhaul MRO Organisation Production Airline B
C	OEM Airbus Logistics Services Provider MRO Organisation Inventory MRO Organisation Component Overhaul MRO Organisation Production Airline A
D	OEM Airbus Logistics Services Provider MRO Organisation Inventory MRO Organisation Component Overhaul MRO Organisation Production Airline B

Fig. 3 indicates a typical transaction workflow for channel C, which involves interactions between six client applications and six peers from the respective organisations with ledger C. In the beginning, each client application generates a transaction proposal, which is sent to every peer for endorsement. For example, client application A1 has generated a transaction T1 proposal P and sends it to all the peers on channel C. The endorsing peer will act on the transaction proposal and execute the chaincode to create a response for the transaction proposal. The peer shall endorse the proposal response by signing the payload using its private key, known as its *digital signature*. For example, OEM Airbus runs its chaincode using the transaction T1 proposal P and generates a response R1 with an endorsement, E1. This process is also applied to all the peers related. Once the client applications have enough responses from the sets of peers, the first step of the transaction flow has completed. The consensus has been achieved, since each organisation in the channel has endorsed the proposed ledger change.

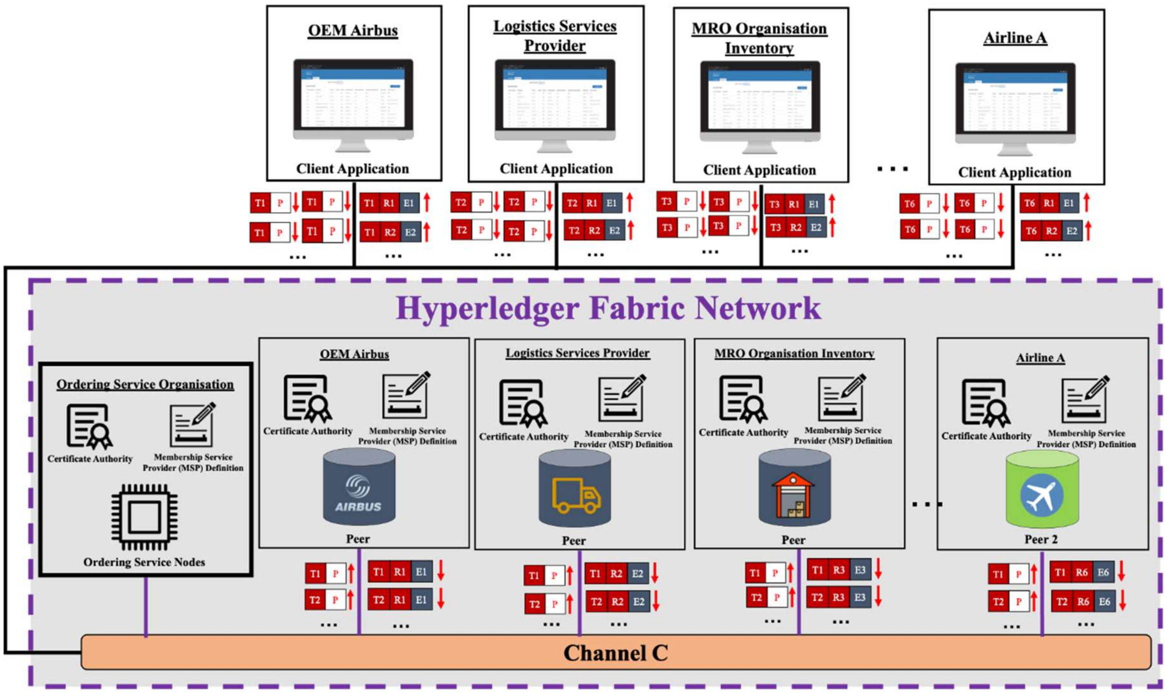


Fig. 3. Transaction Proposal.

After all endorsements of the transaction proposal have been received, as is shown in Fig. 4, the client applications shall send all their completed transaction proposals concurrently to the ordering server node. For example, the client application of OEM Airbus sends the transaction T1 to the ordering service nodes with the response from the peers, endorsed by E1, E2 ... E*n*. This process is applied to other client applications from other organisations. The node will further arrange the submitted transaction in the sequence strict order of T1, T2, T3, T4, T5, T6, with the channel configuration parameters (i.e., maximum elapsed duration and desired block size) and further encryption into a single-transaction hash value as shown in the figure. The structure of the hash value of the previous block, timestamp, hash value of the key-value store, and the transaction hash value will package a new block that is ready for addition into the ledger of each organisation in channel C. Once the final block is generated, all validated transactions will be immutable with no ledger forks.

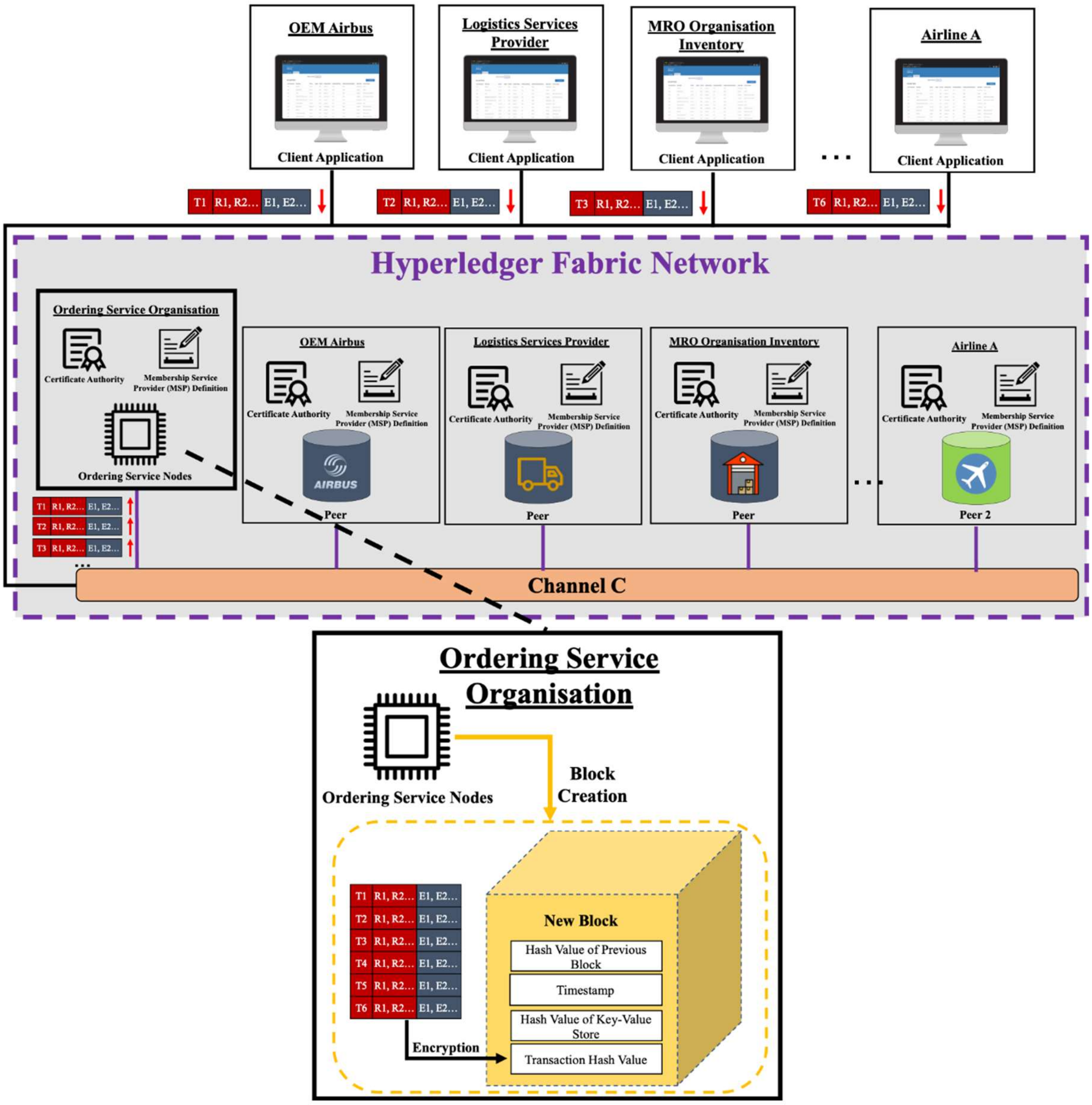


Fig. 4. Ordering and Packing Transactions Into the Block.

Since all transactions are validated with consistent responses and endorsements from the respective peers, the block should be able to distribute and commit the ledger from the ordering service node to the peers. For example, in Fig. 5, the ordering service node distributes the new block to all peers from OEM Airbus, logistics services provider, MRO organisation inventory, MRO organisation component overhaul, and MRO organisation production. The peer will then perform the ledger consistency check to verify the ledger compatibility status. Based on the endorsement police of the chaincode, the block will be validated and added independently to the ledger of respective organisations, which consistently shares updates with other peers. The peer can still reject the block addition for any violation of the endorsement policy to ensure the identical result and outcome from other peers. The client application will receive a block even notification, which only includes the information summary of the block validation once the transaction has been processed and the overall blockchain operation has been completed.

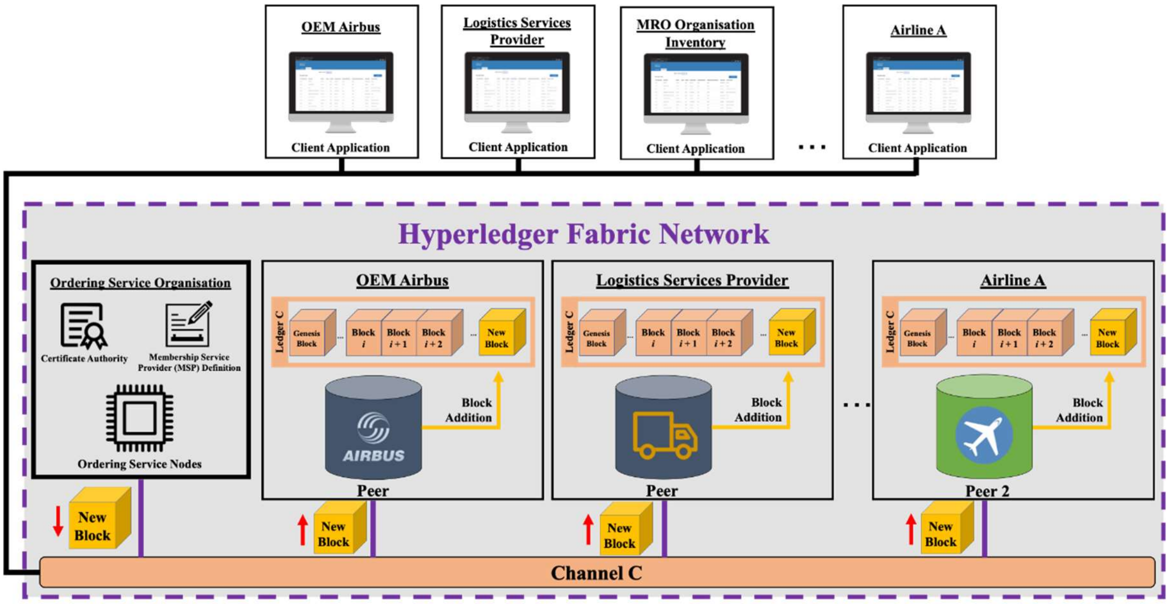


Fig. 5. Validation and Commit.

3.4. Digital Twins in a Blockchain-Based System

After the validation of transactions and endorsement, the aviation spare parts inventory is recorded and made immutable. Therefore, the blockchain-based system also acts as an anti-counterfeiting digital twin to ensure all the processes in the inventory management have not been tampered with. We propose that in the cyberspace of the aviation industry, the stakeholders in the network, including the OEMs, MRO organisations, logistics services providers, and airlines, can also form multiple twins (Leng et al., 2021). The digital twin network can be designed to be incorporated with the proposed inventory management blockchain network and other digital tools such as virtual reality (Tang et al., 2020a) and mixed reality (Tang et al., 2018, 2020b) to simulate, visualise, and interact with the status of the inventory process in cyberspace.

The physical space of the processes can be embedded with IoT sensors, including RFID, to visualise the logistics status and aircraft parts signatures for security, as well as real-time synchronisation of equipment level for parallel control of various smart workshops (Leng et al., 2019b). For instance, in the manufacturing execution system for production management, the cyber–physical connection can be incorporated into the metal additive manufacturing process for the part manufacturing of an OEM in the aircraft industry (Madolla et al., 2019). It can also be established to form a dynamic autonomous system for packing and storage assignment in the large-scale warehouse of a logistics service provider for aircraft parts (Leng et al., 2019c). The blockchain network ensures the security of the whole process, as well as the traceability and trackability of the spare parts and components. The incorporation of digital twins and blockchain networks not only enables the visualisation of the current status of the production equipment and logistics process but can also predict its trend for inventory forecasting by analysing the context via the learned operating behaviour patterns in the inventory logistics process of aviation.

4. Results

4.1. Implementation With Hyperledger Composer

The tools used to implement the proposed blockchain-based system are details in Table 3 with respective configuration versions, and all applications were carried out using macOS Big Sur version 11.0.1 with a 2.3 GHz Intel Core i9 processor and 16 GB memory. The docker-compose (v1.24.1) and engine (v19.03.1) served as the back-end environment and container configuration of the system. Node (v8.17.0) and Python (v2.7.16) are the prerequisites for developing the client SDK and the Hyperledger Fabric (v1.2) network. The Hyperledger composer-playground enabled the design of the business network definition with assets, participants, and transactions. The Composer REST server provided the blockchain platform, which processed and visualised all back-end business logic to the front-end user interface platforms, for example, an Angular web application. The Angular application, programmed using HTML, CSS, and JavaScript, can trigger the HTTP method and make HTTP requests to the REST API Server.

Table 3

Tools for Proposed System Implementation

System Component	Description
IDE	composer-playground
Hyperledger Fabric	v1.2
Node	v8.17.0
CLT Tool	Composer REST Server
Docker-Engine	19.03.1
Docker-Compose	1.24.1
Python	2.7.16
CPU	Intel Core i9 @ 2.3 GHz
Operating Systems	macOS Big Sur Version 11.0.1
Memory	16 GB
Programming Language	HTML, CSS, JavaScript
Browser	Google Chrome, Firefox, Safari

Hyperledger Composer is an open development and extensive toolset for creating blockchain applications that are easy to integrate and model with existing business systems. It supports the Hyperledger Fabric runtime and infrastructure with pluggable blockchain consensus protocols that ensure the validation of transactions between the designed business network participants. During the blockchain network design with the Composer, the primary business network should be defined in the associated coding files. The *model file* contains the basic descriptions of assets, participants, and transactions. The *assets* of the proposed system are the general and certification information of the aircraft spare parts and logistics delivery. The *participants*, who run the business and network and have assets to performance transactions, are the OEM, the departments of MRO organisation, logistics services provider, and the air operator. The *script file* contains the transaction functions and execution procedures, known as the *smart contract* and *chaincode* in Hyperledger Fabric, for assets and participants interaction and transactions. An example algorithm for aircraft parts damage reporting is shown in Algorithm 1. The *access control file* includes the access control rules for each participant, which define who can read, write, and perform specified transactions. It is an effective method for giving limited participant access to the blockchain system. All these files will go into a single business network achieve for Hyperledger Fabric deployment.

The primary objective of the blockchain network is to store the information in a distributed way, in which each block contains an encrypted transaction and hash functions for information security purposes. The service-oriented system architecture provides smart contract, security, and integrity management features under the distributed ledger manner with the design is shown in the figure. The end-user of the system (e.g., the airline, MRO component overhaul, MRO inventory, MRO production, OEM, or logistics services provider) can perform specified transactions using the front-end Angular web application in each process of the aircraft parts management. Each user can also track the latest status and certification process by performing the HTTP request through the front-end application to the REST API server. The REST API server will automatically trigger the consensus algorithms and smart contract when the predefined business terms and conditions regarding computer code have been met. Furthermore, the smart contract also facilitates the users in asset management access rights in the distributed ledger of the blockchain platform. The successful execution of the smart contract and consensus algorithms will lead to the ledger update of the aircraft spare parts and synchronised to the Hyperledger Fabric network.

As mentioned, the client application is designed to allow each participant of the blockchain network to perform transactions and HTTP requests through the connection to the REST API server. The REST API server will process, store, and distribute every successful transaction in the Hyperledger Fabric network. A monitoring page is attached to all organisations' client applications for the continuous monitoring of the aircraft parts' condition and certification information, facilitating a better simulation of the actual working environment. Any successful transactional updates will automatically synchronise with all organisation's interfaces. A data entry form for the OEM Airbus admin to create a new Aircraft Parts Certificate for new aircraft spare parts. After submission, the Fabric network will automatically register the declared information as an asset identified by serial number. The serial number is needed for any further parts updates using transactional functions. The Parts Damage Reporting transactional function, shown in Fig. 6, is used in the case that any damage was found during the regular audit check.

```
Input:     P/N                      Part Number;
           S/N                      Part Serial Number;
           ProcessName/Details      Information and details about all process involved;
           AduitReports             Audit-quality reports done;
           TestProcedures           Test procedures and reports done;
           QualityData              Quality certification data of the part;
           ReasonForRecordEntry     Reason for a Record Entry;
           Reference                Name of approval document;
Output:    Aircraft part information updated with reported damage
           Generate identity key transactionKey by S/N;
           Get transaction(tx) by transactionKey;
           If (P/N match) then
                    If (S/N match) then
                         Get Asset Registry of Asset Aircraft Part from Hyperledger Composer;
                         Await Asset Registry to Update the New Information for 'S/N' Aircraft Part;
                         Create a New Event for transaction 'Aircraft Parts Damage Reporting';
                         Update old and new variables of the Aircraft Part Information;
                         Emit Event;
                         Return Success;
                         end If
                    else
                         Return "Error";
                    end If
           else
                    Return "Error";
           end If
```

Fig. 6. Example of the Parts Damage Reporting Transactional Function Algorithm.

Fig. 7 provides a log of all systems and transactions in the Hyperledger Fabric network. It is attached to all organisations' user interfaces for an identical copy of encrypted and unique transaction IDs, which enhances information security. The users of the client application are unable to alter and review the details of previous transactions. Determining the asset information changes of the initial transaction is based on the transaction type and the associated transaction ID, selecting the system historian through the REST API server, and entering the transaction ID in the value box. The response body will display the "event emitted" data sets, which contain both previous and new asset values shown in red.

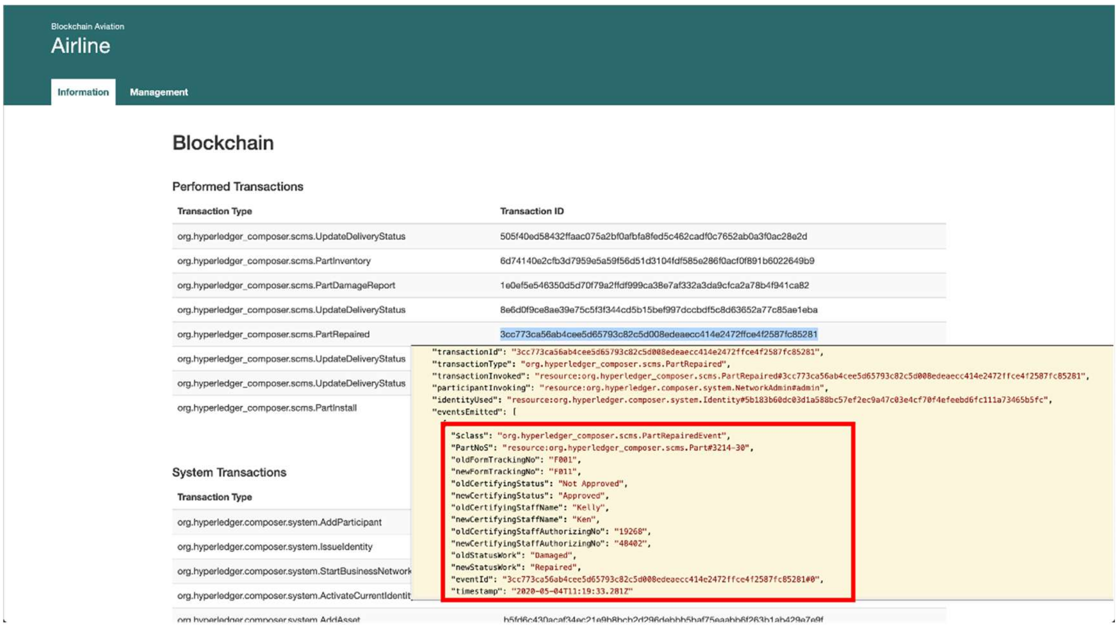


Fig. 7. Performed and System Transactions Log.

This decentralised blockchain network works successfully by connecting Hyperledger Fabric and Angular web interface to improve the efficiency and the quality of the aircraft parts management. Nowadays, aircraft maintenance required a lot of paperwork and communication between companies. It takes too much time for complicated processes, which is not cost-effective. Nevertheless, applying the whole process in the blockchain network can simplify the current inventory management procedures. Also, networking can improve the neatness of the data that companies can store all the different information in the same highly secure network.

4.2. Sensitivity Analysis

The deployed blockchain system with the management of assets and transactions has provided a positive effect in terms of aircraft spare parts history tracking and continuous monitoring. Since the information processing and blocks forging is run under the REST API server and further distributed to the Fabric network, it is crucial to test the efficiency and performance of the REST API server when handling a large number of users and further determine the system capacity with the block synchronisation of the fabric network. Performance indicators, including response latencies, hits per second, transaction time, and response time, depending on the number of active threads, are examined with ten groups of active threads, a computational time of 6,000 seconds, and an infinite loop count during simulations. All results were obtained using Apache JMeter and conducted in a macOS Big Sur environment with a 2.3 GHz Intel Core i9 and 16 GM RAM.

The complete performance results of response latencies over time with moving averages are detailed in Appendix A. Table 4 shows linear relationships between the number of active threads, the mean response latencies, and response latencies standard deviation. Both mean response latencies and their standard deviations depend on the number of threads. The indicated linear equation can enable further determination of the latency values based on the number of active users of the blockchain application.

Fig. 8 indicates the results of the sensitivity analysis. The *hits per second* is the number of HTTP requests sent by the threads to the REST API server. A *transaction* is a group of requests in the test terminology that can create multiple hits to the server. The results of all threads sets are combined, and the overall fluctuation ranged between 50,000 to 60,000 hits per second within the 6,000 seconds of testing. The performance of transactions through and response time are dependent on the number of threads. It further illustrates the mean 5,000 transactions through per second after 210 threads.

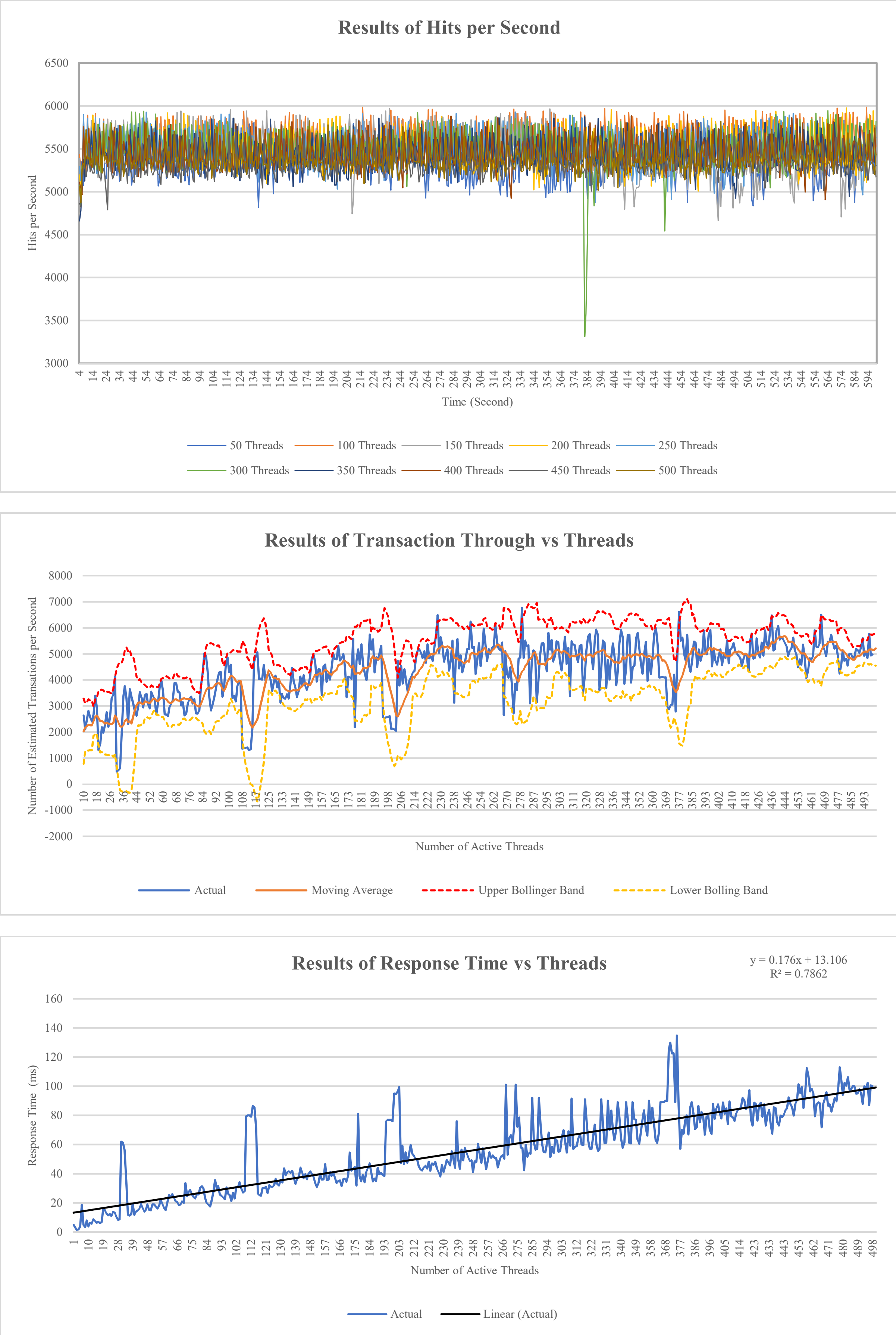


Fig. 8. Results of Sensitivity Analysis.

Table 4
Analysis of Response Latency Performance

Number of Active Threads	Mean Response Latencies (ms)	Standard Deviation
50	8.97	0.59
100	17.65	1.16
150	26.80	1.77
200	35.51	2.36
250	44.38	2.82
300	53.82	3.42
350	63.33	3.97
400	72.51	4.85
450	83.21	5.60
500	91.42	6.26
Linear Equation	$y = 0.1832x - 0.7754$	$y = 0.0126x - 0.1164$
R-Square Value	0.9995	0.9944

5. Discussion

The result of the sensitivity analysis is to prove that the blockchain-based system has practical implications for the existing ASPM with essential system requirements mentioned by Wickboldt & Kliewer (2019). The implemented system is capable of merging events from different sources with access authorisations and mapping rules of the business process. The transaction can be executed immediately, and the system can also handle a throughput of over 2,000 transactions per second (tps) within the Hyperledger Fabric network, which is much greater than the 0.16 tps requirement.

Through the proposed blockchain-based system, all the stakeholders in the spare parts supply chain can perform transactions and communicate securely. The proposed Hyperledger Fabric network has aimed to connect each organisation and heighten efficiency during aircraft parts transactions. All related organisations can share and receive the data through the system, which reduces costs, communication time, and documentation in tracing and tracking aircraft parts. Organisations using a single system with a security information sharing mechanism shall mitigate the lack of interoperability in the existing supply chain. The significant benefit of traceability enables MRO organisation to trace spare parts status with reduced influence of incorrect information display through consensus from another participated organisation. It will further benefit airlines in preventing the situation of AOG by ensuring the MRO organisation has serviceable spare parts. Thus, it avoids financial loss for airlines during AOG situations and MROs losing airline customers because of maintenance issues. Information transparency and visibility enable better planning in ASPM with reduced parts tracing time, and faster response improves the efficiency amount the maintenance work.

Since the confidentiality of spare parts information is critical to attractiveness and reputation in the market, the security of the data is an essential element in designing the Hyperledger Fabric network. Channels are designed between each joining organisation to ensure information security and credibility. Organisational peers can communicate freely within their responsible channels; peers without the channel's certification are not allowed to enter and read the information inside it. Each signal peer can have more than one channel to convince them to connect with serval peers. All the transaction records are saved in the ledger, where every participant within the channel owns a copy. For every transactional operation, the ledger will be updated with data encryption and access control.

Spare part tracing and tracking are not simple tasks within the ASPM. The aviation industry operates in a strict supervisory environment that requires inspection and certification of all components used by any aircraft. However, many spare parts are resold numerous times, increasing the challenge of tracking their history. Aircraft maintenance issues and errors are the main causes of aircraft accidents. The maintenance records may be lost and destroyed over time; this makes the task of the investigator more difficult. However, the proposed blockchain system can disclose the history quickly and clearly of each spare part as it is appropriately stored in the network. It raises the efficiency and accuracy in ASPM so that certifiers and other accountable personnel can read the maintenance details and discover the reason for an accident more quickly.

6. Conclusion

This paper has proposed a blockchain-based system for aircraft spare parts traceability and condition tracking from OEM throughout the supply chain. The presented data model and system architecture design with Hyperledger Fabric has integrated the ASPM scenario and enables secure and adequate information sharing through the consensus and channels mechanism. The blockchain-based system deployed using Hyperledger Composer has demonstrated effective transaction processing with significant system sensitivity capacity. An evaluation of traceability, condition tracing, and information security has been included in this paper. These lead to the conclusion that the proposed system could enhance information visibility, quality traceability data, and information sharing between organisations in the spare parts supply chain.

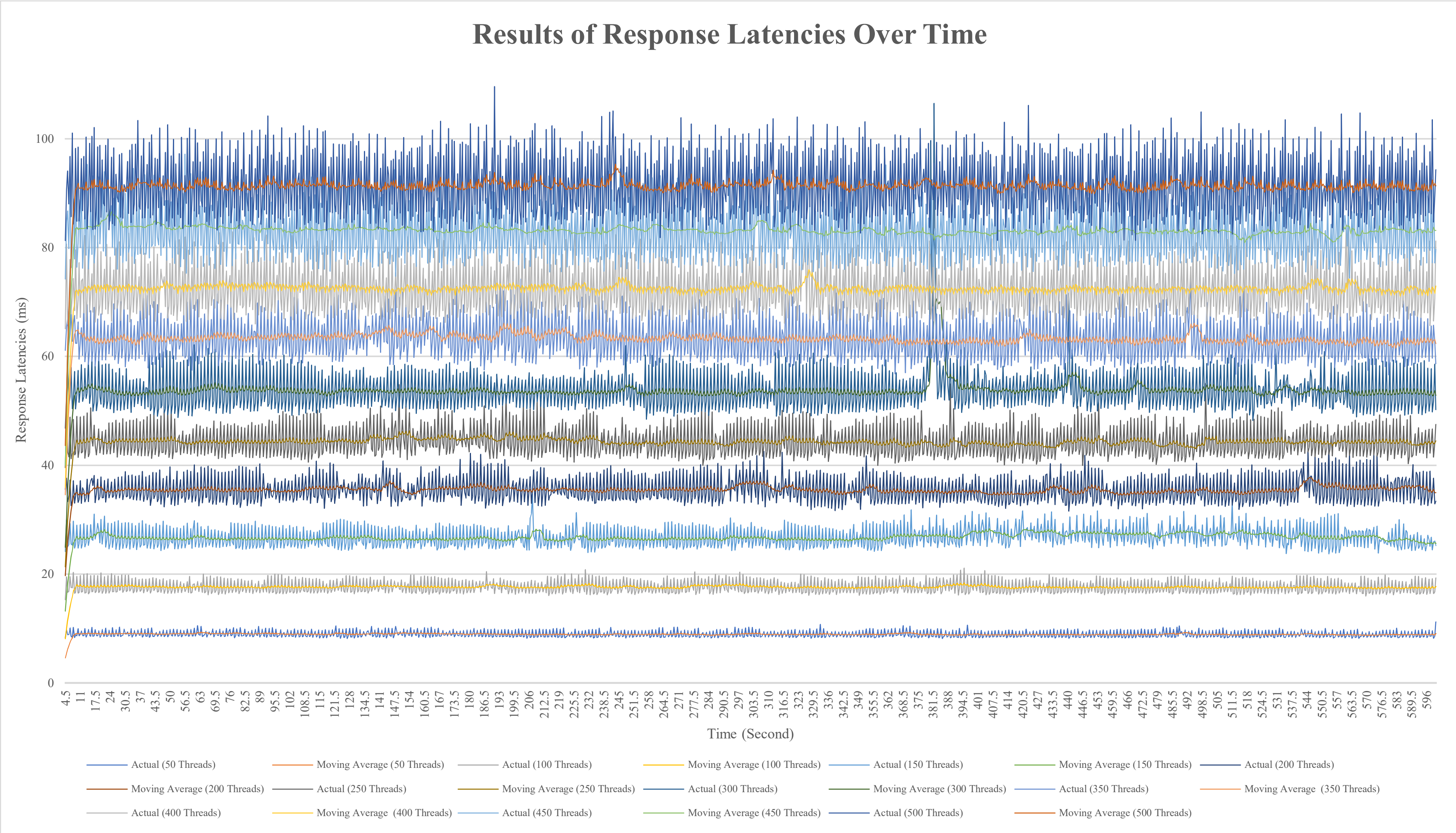
The article also illustrates a framework for integrating the digital twins in the proposed blockchain-based system. Nevertheless, this research still has some limitations that can be improved upon. First, the framework of integrating the digital twins in the blockchain system is still in an early stage. Further work can be implemented to formulate the data collection strategies for all twins. On the other hand, since the blockchain solution proposed in this paper focuses on information recording, there data analytics can potentially be integrated with the system. For example, statistical functions can be designed to calculate the number of damages that happened in each species and the life cycle of parts. Therefore, the OEM and MRO organisation can have a future investigation by checking these records and improve the reliability performance of spare parts. The inventory department can benefit from controlling the number of purchases and achieve just-in-time inventory management, which can minimise inventory and increase efficiency. The overall ASPM can be shortened with less capital spending on raw materials as the parts are just enough for planned maintenance operations. Lastly, the traceability and trackability of the spare parts were demonstrated by developing a blockchain-based system and tested with the sensitivity analysis; the performance measures were not collected in physical spaces. Future research can be performed to collect real data by implementing the digital twins with the proposed blockchain network. This not only allows the verification can be done through physical data but also enables those data to be analysed further. Therefore, in the future, we propose the proposed blockchain-based system can be extended to other domain applications. Further research can also be conducted to integrate deep learning and forecasting algorithms into the blockchain-based system and the cyber–physical space to form a secure and decentralised digital twin network for aircraft spare parts inventory forecasting.

ACKNOWLEDGEMENT

The authors would like to thank the Research Grants Council of Hong Kong for supporting this research under the Grant UGC/FDS14/E06/19.

APPENDIX

Performance of Response Latencies Over Time



REFERENCES

Alain, C., & Mashhor, A. (2014). ICAO Doc 9760 (Airworthiness Manual), 3rd Edition-2014.

Aleshi, A., Seker, R., & Babiceanu, R. F. (2019). Blockchain Model for Enhancing Aircraft Maintenance Records Security. *2019 IEEE International Symposium on Technologies for Homeland Security,* 1-7.

Alharby, M., & van Moorsel, A. (2017). Blockchain Based Smart Contracts : A Systematic Mapping Study. *2018 International Conference on Cloud Computing, Big Data and Blockchain (ICCBB)*, 125-140. 10.5121/csit.2017.71011.

Bas de Vos. (2017). Using Blockchain To Reinforce Aviation Asset Management. *Aircraft Maintenance Technology,* 28(9), 54-55.

Chan, C.C.J., Balasubramanian, S. and Charmaine, N., 2020. A systematic literature review on the benefit-drivers of RFID implementation in supply chains and its impact on organizational competitive advantage. *Cogent Business & Management*, 7(1), p.1818408.

Chang, Y.S, Chang, H.O., Whang, Y.S., Lee, J.J, Kwon, J.A, Kang, M.S, & Park, J.S. (2006). Development of RFID enabled aircraft maintenance system. *Proceedings of IEEE International Conference on Industrial Informatics, Singapore,* 224-229.

Choi, S.H., Yang, B., Cheung, H.H., & Yang, Y.X. (2015). RFID tag data processing in manufacturing for track-and-trace anti-counterfeiting. *Computers in Industry, 68*, 148-161.

Dominique, T. & Sothearath S. (2019). Proof of Work and Proof of Stake consensus protocols: a blockchain application for local complementary currencies, Working Papers halshs-02268391, HAL. https://ideas.repec.org/p/hal/wpaper/halshs-02268391.html

Falazi, G., Hahn, M., Breitenbücher, U., Leymann, F. & Yussupov, V. (2019). Process-Based Composition of Permissioned and Permissionless Blockchain Smart Contracts, *2019 IEEE 23rd International Enterprise Distributed Object Computing Conference (EDOC)*, Paris, France, 77-87, doi: 10.1109/EDOC.2019.00019.

Fescioglu-Unver, N., Choi, S.H., Sheen, D., Kumara, S., Misic, V. B., Lang, K. R., & Zhao, J. L. (2015). RFID in production and service systems: Technology, applications and issues. *Information systems frontiers, 17*(6), 1369-1380.

Helo, P., & Hao, Y. (2019). Blockchains in operations and supply chains: A model and reference implementation. *Computers & Industrial Engineering, 136*, 242-251.

Hensel, J., Jazz Aviation - Paperless Maintenance Processes. Retrieved October, 2017, from https://www.aircraftit.com/MRO/eJournals/eJournal/Aircraft-IT-MRO-SeptemberOctober-2017/Reviews/Jazz-Aviation-Paperless-Maintenance-Processes.aspx

Holmström, J., Kajosaari, R., Främling, K., & Langius, E. (2009). Roadmap to tracking based business and intelligent products. *Computers & Industrial Engineering,* 60, 229–233.

IATA (2015). *Best Practices for Component Maintenance Cost Management.* International Air Transport Association.

ICAO (2015). ICAO Journal News and Developments From the International Civil Aviation Organization, 70(2), 9.

Keivanpour, S., & Kadi, D.A. (2019). The Effect of "Internet of Things" on Aircraft Spare Parts Inventory Management, *IFAC-PapersOnLine*, 52(13), 2343-2347, https://doi.org/10.1016/j.ifacol.2019.11.556.

Korpela, K., Hallikas, J., & Dahlberg, T. (2017). Digital Supply Chain Transformation toward Blockchain Integration. *Hawaii International Conference on System Sciences,* 50.

Lazarevic, M., Ostojic, G., Cosic, I., Stankovski, S., Vukelic, D., & Zecevic, I. (2011). Product lifecycle management (PLM) methodology for product tracking based on radio-frequency identification (RFID) technology. *Scientific Research and Essays, 6*(22), 4776-4787.

Leng, J., Zhang, H., Yan, D. et al. (2019a). Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop. *J Ambient Intell Human Comput*, 10, 1155–1166. https://doi.org/10.1007/s12652-018-0881-5

Leng, J., Yan, D., Liu, Q., Zhang, H, Zhao, G, Wei, L., Zhang, D., Yu A., Chen, X. (2019b). Digital twin-driven joint optimisation of packing and storage assignment in large-scale automated high-rise warehouse product-service system. *International Journal of Computer Integrated Manufacturing*, DOI: 10.1080/0951192X.2019.1667032

Leng, J., Jiang, P., Xu, K., Liu, Q., Zhao, J.L., Bian, Y., Shi, R. (2019). Makerchain: A blockchain with chemical signature for self-organizing process in social manufacturing. *Journal of Cleaner Production*, 234, 767-778. https://doi.org/10.1016/j.jclepro.2019.06.265

Leng, J., Ruan, G.L., Jiang, P.Y., Xu, K.L., Liu, Q., Zhou, X.L., Liu, C. (2020a). Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey. *Renewable and Sustainable Energy Reviews*, 132(C).

Leng, J., Zhou, M., Zhao, J.L., Huang, Y., Bian, Y. (2020b). Blockchain Security: A Survey of Techniques and Research Directions. *in IEEE Transactions on Services Computing*, doi: 10.1109/TSC.2020.3038641.

Leng, J. et al. (2020c). ManuChain: Combining Permissioned Blockchain With a Holistic Optimization Model as Bi-Level Intelligence for Smart Manufacturing. *in IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 50(1), 182-192, Jan. 2020, doi: 10.1109/TSMC.2019.2930418.

Leng, J. et al., (2021). Blockchain-Secured Smart Manufacturing in Industry 4.0: A Survey. in IEEE Transactions on Systems, Man, and Cybernetics: Systems, 51(1), 237-252, Jan. 2021, doi: 10.1109/TSMC.2020.3040789.

Lin, L., Luo, B., & Zhong, S. (2017). Development and application of maintenance decision-making support system for aircraft fleet. *Advances in engineering software, 114*, 192-207.

Lin, J., Shen, Z.Q., Zhang, A. & Chai, Y.T. (2018). Blockchain and IoT based Food Traceability for Smart Agriculture. *In Proceedings of the 3rd International Conference on Crowd Science and Engineering (ICCSE'18)*. Association for Computing Machinery, New York, NY, USA, Article 3, 1–6. DOI:https://doi.org/10.1145/3265689.3265692

Madolla, C., Messeni Petruzzelli, A., Percoco, G., Urbinati, A. (2019). Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis into the aircraft industry. *Computers in Industry,* 109, 134-152.

Masood, F. & Faridi, A. (2018). An Overview of Distributed Ledger Technology and its Applications. *International Journal of Computer Sciences and Engineering*, 6. 422-427. 10.26438/ijcse/v6i10.422427.

Mostafa, S., Lee, S., Dumrak, J., Chileshe, N., & Soltan, H. (2015). Lean thinking for a maintenance process. *Production & manufacturing research, 3*(1), 236-272.

Nakamoto, S. (2008) *Bitcoin: A Peer-To-Peer Electronic Cash System*.

Nawari, N. O., & Shriraam, R. (2019). Blockchain and the built environment: Potentials and limitations. *Journal of Building Engineering, 25*, 100832.

Ng, T.J., Wong, M.M., Zhang, J.B., & Gan, O.P. (2006). RFID for MRO Work in Progress Tracking. *In Proceedings of the IECON 2006—32nd Annual Conference on IEEE Industrial Electronics*, 4779–4784.

Ngai, E., Cheung, B., Lam, S. & Ng, C.T. (2014). RFID value in aircraft parts supply chains: A case study. *International Journal of Production Economics*. 147. 330-339. 10.1016/j.ijpe.2012.09.017.

Ramudhin, A., Paquet, M., Artiba, A., Dupré, P., Varvaro, D., & Thomson, V. (2008). A generic framework to support the selection of an RFID-based control system with application to the MRO activities of an aircraft engine manufacturer. *Production planning & control, 19*(2), 183-196.

Resende-Filho, M., & Hurley, T. (2012). Information asymmetry and traceability incentives for food safety. *International Journal Of Production Economics*, 139(2), 596-603. doi: 10.1016/j.ijpe.2012.05.034

Sahay, A. (2012). *Leveraging Information Technology for Optimal Aircraft Maintenance, Repair and Overhaul (MRO).* 10.1533/9780857091437.

Santonino III, M., Koursaris, C., & Williams, M. (2018). Modernizing the Supply Chain of Airbus by Integrating RFID and Blockchain Processes. *International Journal of Aviation, Aeronautics, and Aerospace, 5*(4), 4.

Saygin, C., & Tamma, S. (2012). RFID-enabled shared resource management for aerospace maintenance operations: A dynamic resource allocation model. *International Journal of Computer Integrated Manufacturing, 25*(1), 100-111.

Tang, Y.M., Au, K.M., & Leung, Y. (2018). Comprehending products with mixed reality: Geometric relationships and creativity. *International Journal of Engineering Business Management*, 10, 1847979018809599. https://doi.org/10.1177/1847979018809599

Tang, Y.M., Au, K.M., Lau, H.C.W. et al. (2020). Evaluating the effectiveness of learning design with mixed reality (MR) in higher education. *Virtual Reality*, 24, 797–807 (2020). https://doi.org/10.1007/s10055-020-00427-9

Tang, Y.M., Ng, G.W.Y., Chia, N.H., So, E.H.K., Wu, C.H., Ip, W.H. (2020). Application of virtual reality (VR) technology for medical practitioners in type and screen (T&S) training. *J Comput Assist Learn.*, 2020; 1– 11. https://doi.org/10.1111/jcal.12494

Global Aviation MRO Logistics Market - Use of Blockchain to Promote Growth: Technavio. (2018, April 21). Retrieved from https://www.businesswire.com/news/home/20180421005046/en/Global-Aviation MROLogistics- Market---Blockchain

Wang, C., & Li, B. (2019). Research on Traceability Model of Aircraft Equipment Based on Blockchain Technology. *2019 IEEE 1st International Conference on Civil Aviation Safety and Information Technology,* 88-94.

Wang, K.S. (2014). Intelligent and integrated RFID (II-RFID) system for improving traceability in manufacturing. *Advances in Manufacturing, 2*, 106–120.

Wickboldt, C., & Kliewer, N. (2019). BLOCKCHAIN FOR WORKSHOP EVENT CERTIFICATES -A PROOF OF CONCEPT IN THE AVIATION INDUSTRY. *Twenty-Seventh European Conference on Information Systems.* 1-15.

Yang, S., Crisp, M., Penty, R.V., & White, I.H. (2018). RFID Enabled Health Monitoring System for Aircraft Landing Gear. *IEEE Journal of Radio Frequency Identification, 2*(3), 159-169.

Yongquan, S., Xi, C., He, R., Yingchao, J., & Quanwu, L. (2016). Ordering decision-making methods on spare parts for a new aircraft fleet based on a two-sample prediction. *Reliability engineering & system safety, 156*, 40-50.

Zhai, S., Yang, Y., Li, J., Qiu, C., Zhao, J. (2019). Research on the Application of Cryptography on the Blockchain. *J. Phys. Conf. Ser.*, 1168, 032077.

Zheng, P., Wang, J.L., Zhang, J., Yang, C.Q. & Jin, Y.Q. (2019). An adaptive CGAN/IRF-based rescheduling strategy for aircraft parts remanufacturing system under dynamic environment, *Robotics and Computer-Integrated Manufacturing*, 58, 230-238, https://doi.org/10.1016/j.rcim.2019.02.008.