DEVELOPMENT OF A BLOCKCHAIN-ENABLED IOT SYSTEM FOR PERISHABLE FOOD E-FULFILMENT

TSANG YUNG PO

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Development of a Blockchain-Enabled IoT System for Perishable Food E-fulfilment

Tsang Yung Po

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CERTIFICATE OF ORIGINALITY

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TSANG Yung Po (Name of student)

Abstract

In recent years, perishable food e-commerce (PFEC) has offered significant market potential to provide perishable food items (such as fresh fruit, meat and seafood) through online e-commerce platforms. Due to the presence of shelf life and environmentally-sensitive characteristics, the existing e-fulfilment methods cannot fully address to the needs of handling perishable food, even though e-commerce businesses for general commodities are well-developed and standardised. Compared with typical e-commerce businesses, the product quality in PFEC is not only attributable to the vendors themselves, but also to the logistics service providers (LSPs) who provide storage and transportation services. Further, appropriate cold chain management in e-commerce is lacking, resulting in weak customer confidence for PFEC businesses, and a certain likelihood of food deterioration during the e-fulfilment process. On the other hand, end customers in the PFEC environment can only rely on some basic information (such as product descriptions and customer feedback) before purchase. The transparency and traceability regarding perishable food are also limited, which are essential for assisting customer purchasing decisions and food monitoring. Consequently, there is a need for LSPs to improve their existing e-fulfilment methods in the aspects of environmental monitoring, food traceability and food quality management. This will support business development and foster a positive atmosphere in PFEC.

In this research, a blockchain–IoT based multi-temperature e-fulfilment system (BIOMES) is proposed and developed to strengthen the e-fulfilment processes and functionalities when handling food products (which have multiple handling specifications related to environmental conditions) in PFEC. To organise the above concerns in PFEC, three modules in the proposed system are presented: an IoT deployment module (IoTDM), a blockchain data management module (BDMM), and a fuzzy quality management module (FQMM). In essence, the purpose of IoTDM is to structure the deployment of IoT technologies throughout the whole supply chain, by establishing the IoT deployment framework and embedding the concept of traceable resource units (TRUs). Moreover, the deployment scheme of an environmental sensor network is optimised to integrate environmental monitoring and mapping analysis as a whole. Apart from real-time data acquisition, blockchain technology is applied in the BDDM to manage the collected data and formulate food traceability for use in the PFEC environment. The process flow and consensus mechanism of blockchain are customised to align the physical and information flows in the supply chain, and integrate them into the IoTDM cloud. Combining the collected data in IoTDM and BDDM, FQMM provides the three functions on the e-fulfilment process: cold chain passive packaging, multi-temperature delivery route planning, and fuzzy food quality assessment. By doing so, perishable food for completing e-orders can be packed in accordance with the handling specifications, and the maximum time allowed for transportation of packed food can be obtained for enhancing delivery route planning. In addition, the shelf life and quality decay of the food batch can be evaluated in a customised manner for better judgement on the extent of food quality.

The feasibility and performance of the proposed system were validated by conducting two case studies in an LSP, in which one of their business scopes is to explore the market of PFEC in Hong Kong. One of the case studies focused on the handling of fresh fruit, and the other examined meat products for PFEC businesses. Through introducing a generic methodology and implementation roadmap in this research, the case studies examined the flexibility and adaptability of the proposed system when handling different categories of perishable food. Through the pilot runs, improvements in customer-, operation-, and information-related aspects of PFEC businesses were observed.

The major contribution of this research is in the design and development of a blockchain-enabled IoT system with applied artificial intelligence, which strengthens the areas of environmental monitoring, food traceability and food quality management, which are essences in the eco-system of PFEC businesses.

Publications Arising from the Thesis

(**8** international journal papers have been accepted and published, and **1** international paper is under review after major revision. **3** conference papers have been published)

List of International Journal Papers

[1] Tsang, Y.P., Choy, K.L., Wu, C.H., Ho, G.T.S., and Lam, H.Y. (2019). Blockchain-driven IoT for Food Traceability with an Integrated Consensus Mechanism. *IEEE Access*,7(1), pp. 129000-129017.

[2] Tsang, Y.P., Choy, K.L., Wu, C.H., and Ho, G.T.S. (2019). Multi-Objective Mapping Method for 3D Environmental Sensor Network Deployment. *IEEE Communication Letters*, 23(7), 1231-1235.

[3] Tsang, Y.P., Choy, K.L., Wu, C.H., Lam, H.Y., Ho, G.T.S., & Koo P.S. (2019). Bluetooth-based positioning techniques for the cold chain application, *International Journal of Internet Manufacturing and Services*, 6(3), 201-224.

[4] Ho, G.T.S., Tsang, Y.P., Wu, C.H., Wong, W.H., and Choy, K.L. (2019). A Computer Vision based Roadside Occupation Surveillance System for Intelligent Transport in Smart City. *Sensors*, 19(8), 1796. doi: 10.3390/s19081796

[5] Tsang, Y.P., Choy, K.L., Wu, C.H., Ho, G.T.S., Lam, H.Y., & Tang, V. (2018). An intelligent model for assuring food quality in managing a multi-temperature food distribution centre. *Food Control*, 90, 81-97.

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[9] Tsang, Y.P., Choy, K.L., Wu, C.H., Ho, G.T.S., and Lam, H.Y. (2020). Integrating Internet of Things and Multi-temperature Delivery Planning for Perishable Food e-Commerce Logistics: A Model and Application. *International Journal of Production Research*. [Under review after major revision]

List of Conference Papers

[1] Tsang, Y.P., Choy, K.L., Wu, C.H., Ho, G.T.S., and Lam, H.Y. (2019). An Internet of Things (IoT)-based Shelf Life Management System in Perishable Food e-Commerce Businesses. *Proceedings of the Portland International Conference on Management of Engineering and Technology PICMET 2019*, Portland, Oregon, USA, 25-29 August, 2019.

[2] Tsang, Y.P., Choy, K.L., Lam, H.Y., Tang, Valerie, Leung, K.H., & Siu, K.Y. (2017). An Intelligent Route Optimization System for Effective Distribution of Pharmaceutical Products. *Proceedings of the 22nd International Symposium on Logistics ISL 2017*, Ljubljana, Slovenia, 9-12 July, 2017, pp. 394-401.

[3] Tsang, Y.P., Choy, K.L., Poon, T.C., Ho, G.T.S., Wu, C.H., Lam, H.Y., Koo, P.S., & Ho, H.Y. (2016). An IoT-based Occupational Safety Management System in Cold Storage Facilities. *Proceedings of the 6th International Workshop of Advanced Manufacturing and Automation IWAMA 2016*, Manchester, United Kingdom, 10-11 Nov, 2016, pp. 7-13.

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List of Abbreviations

Abbreviation	Full-term
6LoWPAN	IPv6 over Wireless Personal Area Network
AI	Artificial intelligence
ANN	Artificial neural network
API	Application program interface
B2B	Business-to-business
B2C	Business-to-customer
BDDM	Blockchain data management module
BIOMES	Blockchain-IoT-based multi-temperature e-fulfilment system
C2B	Customer-to-business
C2C	Customer-to-customer
CBM	Cubic metres
CFA	Confirmatory factor analysis
Chevalier AOC	Chevalier AOC Freight Express Holdings Limited
CPI	Co-citation proximity index
DoE	Design of experiment
EFA	Exploratory factor analysis
ESCI	Emerging sources citation index
ESN	Environmental sensor network
FEFO	First-expired-first-out
FQMM	Fuzzy quality management module
GA	Genetic algorithm
ICO	Initial coin offering
IoT	Internet of Things
IoTDM	IoT deployment module
IPFS	Interplanetary file system
JSON	JavaScript object notation
KPI	Key performance indicator
LSP	Logistics service provider
LTB	Larger-the-better
M2M	Machine-to-machine
MKRH	Mean kinetic relative humidity
MKT	Mean kinetic temperature

Abbreviation	**Full-term**
MQTT	Message queueing telemetry transport
MTEF	Multi-temperature e-fulfilment
MTK	Multi-response Taguchi-guided k-means clustering
MTKGA	MTK embedded GA
NP-hard	Non-polynomial hard
NSGA-II	Non dominated sorting genetic algorithm-II
NTB	Nominal-the-better
OFP	Order fulfilment process
PaaS	Platform as a Service
PFEC	Perishable food e-commerce
PoA	Proof of authority
PoI	Proof of importance
PoS	Proof of stake
PoSCS	Proof of supply chain share
PoW	Proof of work
QR	Quick response
RFID	Radio frequency identification
RIM	Reference integrity matric
RNs	Relay nodes
RoI	Return on investment
S/N	Signal-to-noise
SCIE	Science citation index expanded
SHA	Secure hash algorithm
SKU	Stock keeping unit
SNs	Sensor nodes
SSCI	Social sciences citation index
STB	Smaller-the-better
TRU	Traceable resource unit
VRP	Vehicle routing problem
WSN	Wireless sensor network
XMPP	Extensible messaging and presence protocol

Chapter 1. Introduction

1.1 Research Background

Global e-commerce businesses have expanded dramatically to provide a number of products and services in recent years, due to their convenience and the changes in customer buying behaviour. According to statistical reports from Statista (Statista, 2019), there are five major categories in retail e-commerce: (i) fashion, (ii) electronics & media, (iii) toys, hobbies & DIY, (iv) furniture & appliances, and (v) food & personal care. As shown in Figure 1.1, the total revenues in retail e-commerce have increased from US$1.7 trillion in 2017 to US$2.9 trillion in 2023, which represents a percentage change of +70%. Also, the categories of (i), (iv), and (v) are fast-growing in the market, with the increases of revenue of 79.2%, 80.2%, and 74.8%, respectively (from 2014 to 2023). To lead the trend of e-commerce development, mobile- and social-commerce are also two emerging channels for developing e-businesses. These create omni-channels of online shopping environments and service packages for customers, adhered to traditional e-commerce platforms. Accordingly, customers and businesses can complete their transactions and deals effectively under four major e-commerce modes: business-to-business (B2B), business-to-customer (B2C), customer-to-customer (C2C), and customer-to-business (C2B) modes (Swani et al., 2014; Zhu, 2015). In view of this, the trades of e-commerce businesses for general commodities have been organised and standardised.

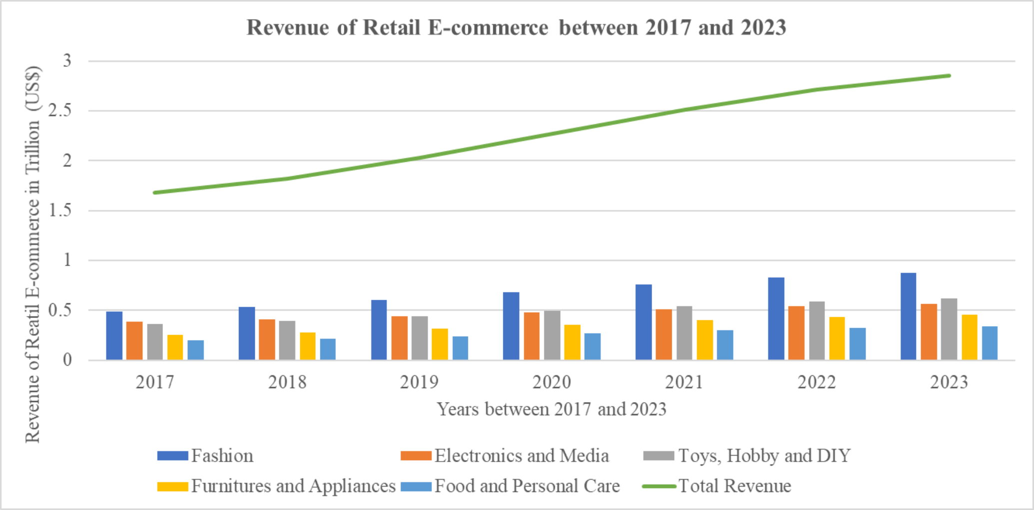


Figure 1.1 Expected revenue of retail e-commerce (Statista, 2019)

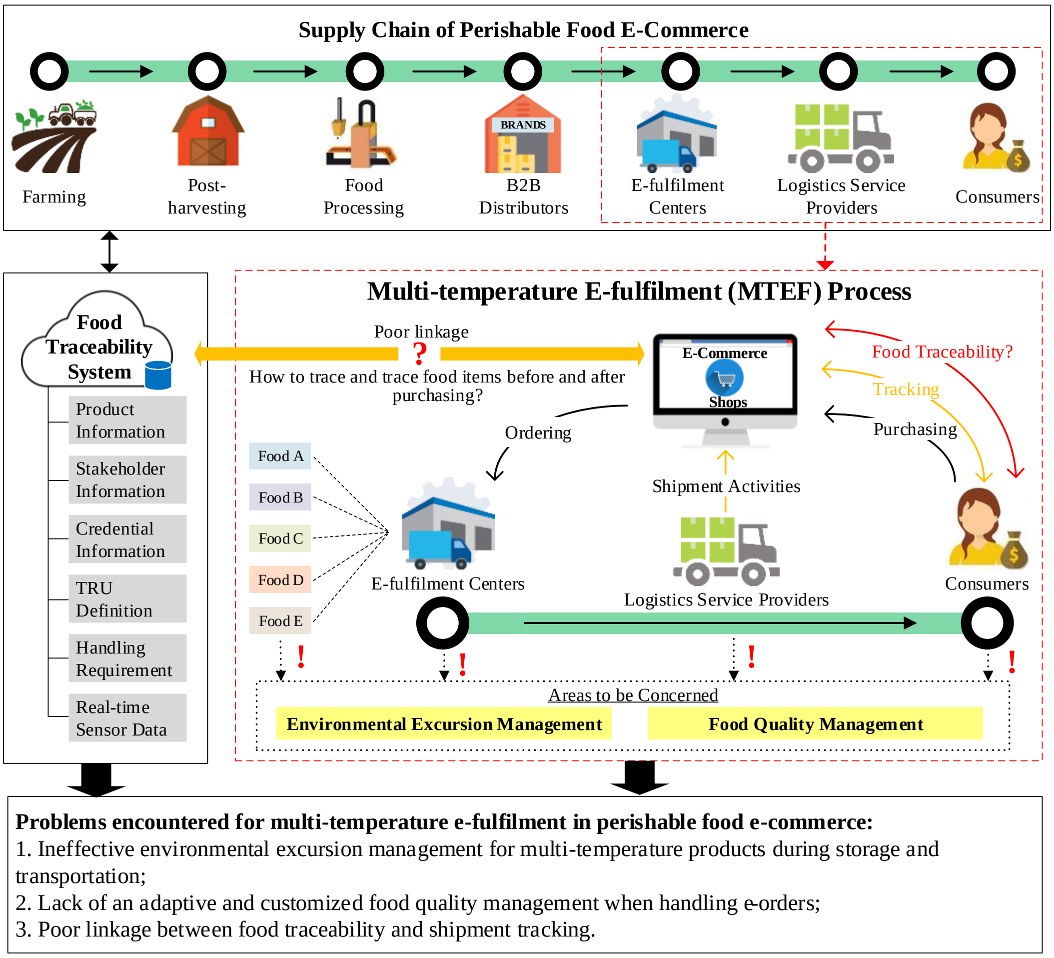
Based on the statistical results in Figure 1.1, among the numerous product categories in e-commerce, food and personal care will be a fast-growing and potential component for e-commerce businesses in the coming years. Particularly, the sales from food and beverage e-commerce are estimated to triple by 2023, and will account for almost 5% of total e-commerce revenue (Packaged Facts, 2019). Thus, the business of perishable food e-commerce (PFEC) has been established to provide a wide range of perishable foods (such as fresh fruit, meat, and seafood) in e-commerce platforms. Even though the PFEC is attractive and profitable, fulfilling customer needs in PFEC is much more challenging and complicated than for other e-commerce products.

Compared with wholesalers in the traditional food supply chain, e-fulfilment centres in PFEC need to consolidate all vendor inventories with multi-temperature characteristics, and maintain an appropriate level of environmental conditions and a designated level of food quality. Consequently, fragmented orders of perishable food with different handling requirements (in terms of temperature and relative humidity) can be handled. Furthermore, existing e-commerce tracking systems, which are designed for recording activities of last mile delivery, are insufficient to evaluate food safety and quality in the entire supply chain. Moreover, due to the presence of shelf life and environmental sensitivity, food items can deteriorate and be contaminated during supply chain activities if there are no appropriate protective and monitoring measures. Therefore, the responsibility of LSPs to maintain food quality for PFEC businesses cannot be neglected. If poor-quality food products are delivered to end customers, the reputation and credibility of the shop would be damaged, and even the e-commerce business of general goods could be affected. Worse still, the eco-system of selling perishable food in the global e-commerce environment might be established negatively, and the trust between customers, vendors, and e-commerce platforms would be broken.

In view of these considerations, this research focuses on multi-temperature e-fulfilment (MTEF) for improving the existing e-fulfilment process when handling multi-temperature food products. The environment of storage and transportation should be controlled and designed for handling multi-temperature food products in a cost-effectiveness manner. In addition, the tracking information to end customers should be enriched, by integrating food traceability to strengthen their confidence in food products and e-commerce platforms. Therefore, this research aims to investigate an intelligent approach, which integrates IoT, blockchain technology, and artificial intelligence to enhance the effectiveness of the MTEF process in PFEC.

1.2 Problem Statements

When integrating the food supply chain and e-commerce logistics, the e-order fulfilment process is newly added to the supply chain to create the previously mentioned MTEF, as shown in Figure 1.2. E-fulfilment centres store food items with multi-temperature requirements in temperature-controlled areas to address two concerns: (i) environmental excursion management, and (ii) food quality management. The monitoring and mapping of environmental conditions in storage areas should be conducted to satisfy the handling requirements, with the considerations of minimal technological deployment costs and maximum system activation. Moreover, for distributing e-orders to end customers, the perishable food should be kept within environmental specifications with minimal cost considerations. Furthermore, to enhance the business environment of PFEC, end customers should be able to track shipment activities and food traceability information to ensure food safety and authentication. Therefore, the linkages of shipment activity tracking system and food traceability system should be considered. When considering the above factors, the three following major problems are identified:



Problems encountered for multi-temperature e-fulfilment in perishable food e-commerce:
1. Ineffective environmental excursion management for multi-temperature products during storage and transportation;
2. Lack of an adaptive and customized food quality management when handling e-orders;
3. Poor linkage between food traceability and shipment tracking.

Figure 1.2 Existing challenges for perishable food e-commerce

(i) Ineffective environmental excursion management in MTEF process

Environmental excursion management, which manages fluctuations of ambient temperature and relative humidity, is essential when handling perishable items in both the storage and transportation areas of PFEC. Different from traditional food storage and transportation, tremendous stock keeping units (SKUs) of food are consolidated in e-fulfilment centres with their own handling specifications. Environmental monitoring and mapping are needed to measure fluctuations in the environmental conditions of storage areas, by adopting wireless sensor technologies. However, existing deployment schemes of wireless sensor networks are not optimised for environmental mapping purposes; hence, these deployments are not cost-effective. For transporting e-orders of perishable food, the design of cold chain packaging should be considered to maintain suitable and stable environmental conditions. However, the formulation of the packaging is not standardised and customised to various food products in the market. Therefore, the overall environmental excursion management is ineffective for striking the balance between cost and performance in the MTEF process.

(ii) Lack of an adaptive and customized food quality management

Apart from recording environmental data in the MTEF process for supporting environmental excursion management, data can be derived to establish food quality management. In the PFEC environment, shelf life and quality decay are two essential factors that help end customers understand the levels of food quality and safety. However, typical methods in food quality management evaluate deterministic shelf life and quality decay, without reacting through supply chain activities. During the PFEC supply chain, there is a certain level of likelihood that the food products can deteriorate, resulting in a reduction of shelf life. Thus, intelligent adjustments on shelf life and quality decay should be considered to comprehend food quality management for PFEC.

(iii) Poor linkage of shipment tracking and food traceability

For operating e-commerce businesses, shipment tracking is one of the key functions of e-commerce systems to visualise shipment journeys and to provide milestones of shipments to customers. In the PFEC, customers are also concerned about information on food traceability and transparency, which reassures them that products to be purchased are safe and suitable. However, existing e-commerce platforms provide a poor linkage of shipment tracking and food traceability, making it difficult for customers to understand the quality and food information completely. Customer confidence in PFEC businesses can be affected without an adequate and comprehensive food traceability and tracking solution.

To summarise, an intelligent and technology-driven approach is needed to solve the aforementioned problems, to create a better atmosphere and eco-system for PFEC businesses. The MTEF process can be improved in the areas of environmental monitoring, food traceability, and food quality management. The directions of improvement in this research are listed below.

a. How IoT deployment schemes for environmental excursion management can be optimised in storage areas;

b. How a secure and reliable data management integrating food traceability and shipment tracking for food chain stakeholders can be developed;

c. How food shelf life and quality decay can be customised and estimated in an intelligent manner for establishing proactive approaches on food quality management;

d. How cold chain packaging for transporting multi-temperature food items can be designed appropriately in last mile delivery.

1.3 Research Objectives

The aim of this research is to explore how emerging technologies, including blockchain, IoT, and artificial intelligence, can be used to enhance the MTEF process in the PFEC environment. The specific objectives of this research are defined as follows:

(i) To propose a three-stage optimisation model for IoT deployment schemes to meet the requirements and compliance of environmental mapping in cold storage areas;

(ii) To propose a blockchain-enabled IoT system that enhances food traceability functionalities, including food identification and data management for perishable food e-commerce businesses;

(iii) To establish an integrated method for estimating food shelf life and quality decay;

(iv) To formulate a cold chain packaging model for handling multi-temperature food products to guarantee designated food quality in last mile delivery.

1.4 Significance of the Research in PFEC

A review of previous literature revealed that e-commerce order fulfilment has been discussed for managing general products, without considering the specific effect of handling perishable food. In practical situations, selling perishable food in e-commerce makes a dramatic change to the e-fulfilment process, such that the ontology of MTEF is proposed in this research to add value to PFEC businesses. The MTEF process is then improved by designing and developing an intelligent and technology-driven system which fulfils customer needs regarding physical and information flows of handling perishable food.

On the other hand, this research is concerned with the design and development of a blockchain–IoT-based multi-temperature e-fulfilment system (BIOMES), to enhance environmental excursion management, food quality management, and food traceability in the MTEF process. There are three facets to the significance of the proposed system.

(i) Intelligent environmental excursion management by IoT technologies

In the past, environment monitoring and mapping were two independent solutions for recording environmental conditions in real-time and analysing critical spots, respectively. However, the mapping results should be applied to drive the deployment of sensor and relay nodes for real-time monitoring. Therefore, a closed-loop control of real-time monitoring is proposed by considering mapping results, together with other essential factors, including costs, system activation time, fault tolerance, coverage and connectivity. Therefore, real-time monitoring and environmental mapping is integrated as a whole through optimising the deployment of a wireless sensor network, resulting in effective environmental excursion management.

(ii) Effective food traceability for perishable food e-commerce businesses

When integrating shipment tracking and food traceability, data management becomes a challenging area when balancing the information provided to customers and the burden of e-commerce systems. The novel deployment of blockchain–IoT data management includes the newly proposed consensus mechanism and tailor-made data flow for MTEF. The purpose of applying blockchain is to manage the key information of food traceability in a secure and reliable manner. Further, blockchain has a lightweight and ‘vaporized’ nature to enhance system scalability and adaptability in PFEC. Therefore, food traceability can be effectively integrated with shipment tracking in e-commerce systems.

(iii) Improved quality control and assurance in METF process

Under the environment of PFEC, the volume and size of e-orders are high and fragmented, respectively. Cold chain packaging is essential to maintain the designated environmental conditions along supply chain activities. However, because of the multi-temperature requirements, using refrigerated trucks to provide a fixed and low temperature cannot cater for all handling requirements. Thus, hybrid/passive cold chain packaging is considered to select different packaging materials to maximise the time available for transporting the perishable food. Such an approach provides the greatest flexibility in last mile delivery for handling multi-temperature products, resulting in better quality control and assurance.

1.5 Thesis Outline

The thesis is divided into seven chapters, and the aspects covered in the dissertation are as follows:

(i) Chapter 1 presents the research problems which exist in the e-fulfilment process of perishable food e-commerce business. The background and motivation for this research are mentioned, while the research objectives and significances are then described.

(ii) Chapter 2 is an academic review to cover the overview and problems of perishable food e-commerce. The differences of e-fulfilment process between perishable food e-commerce and traditional e-commerce are highlighted. The aforementioned challenges and problems can thus be proved. To investigate measures for improvements, artificial intelligence techniques are reviewed, and technologies of blockchain and Internet of Things are analyzed by using co-citation proximity analysis in a semantic manner.

(iii) Chapter 3 includes two main sections. The first section shows the conceptualization of BIOMES. The areas for improvement are focused according to the observed research problems in MTEF process of PFEC. The second section mentions the system architecture of BIOMES, consisting of three major modules, namely (i) IoT deployment module (IoTDM), (ii) blockchain data management module (BDMM), and (iii) food quality management module (FQMM). The blockchain-driven IoT deployment is presented with a newly proposed consensus mechanism. The collected data are then used to support the enhancements of MTEF processes so as to conduct effective and efficient environmental excursion management and food quality assessment.

(iv) Chapter 4 provides a general implementation guide of BIOMES from the system design stage, through structural formation of each module, to the finalized implementation and evaluation stage.

(v) Chapter 5 relates to the deployment of the BIOMES in a Hong Kong-based e-commerce platform to provide a wide range of products sold to end customers. To demonstrate the feasibility of the proposed system, the system deployment includes the e-commerce businesses for fresh fruit and meat to show the genericity of the BIOMES. In addition, the system prototypes of BIOMES are also included to support the illustrations of implementation in the case company.

(vi) Chapter 6 presents the results and discuss the performance of the proposed system. The general discussion of the BIOMES is covered, while the experimental results and discussion regarding case studies are included. By comparing the results from the two case studies, the effectiveness and functionalities of the proposed system can be investigated.

(vii) Chapter 7 draws the conclusion of this research. Also, the contributions of the research work and areas for future research are highlighted.

Chapter 2. Literature Review

2.1 Introduction

The focus of this research is on the design and development of a blockchain-driven IoT system, for strengthening the effectiveness and efficiency of the e-fulfilment process when handling multi-temperature food products, resulting in better supply chain visibility and food quality management. The aim of this section is to provide a comprehensive review for locating real-life challenges and research gaps; hence, appropriate techniques and methods can be suggested to fill these research gaps and address the challenges. The entire framework of the literature review for this research is presented in Figure 2.1. There are four major areas of the literature review: (i) evolution of the food supply chain and e-commerce, (ii) overview of the MTEF process, (iii) semantic similarity review of blockchain–IoT technologies, and (iv) overview of existing artificial intelligence and experimental techniques. The purpose of the first two sections is to explore the background of the PFEC and MTEF processes, to identify the corresponding theoretical and practical challenges when operating a PFEC business. Subsequently, research gaps were deduced in the MTEF process. To fill the identified research gaps, several emerging technologies (including blockchain, Internet of Things, artificial intelligence, and experimental techniques) were studied.

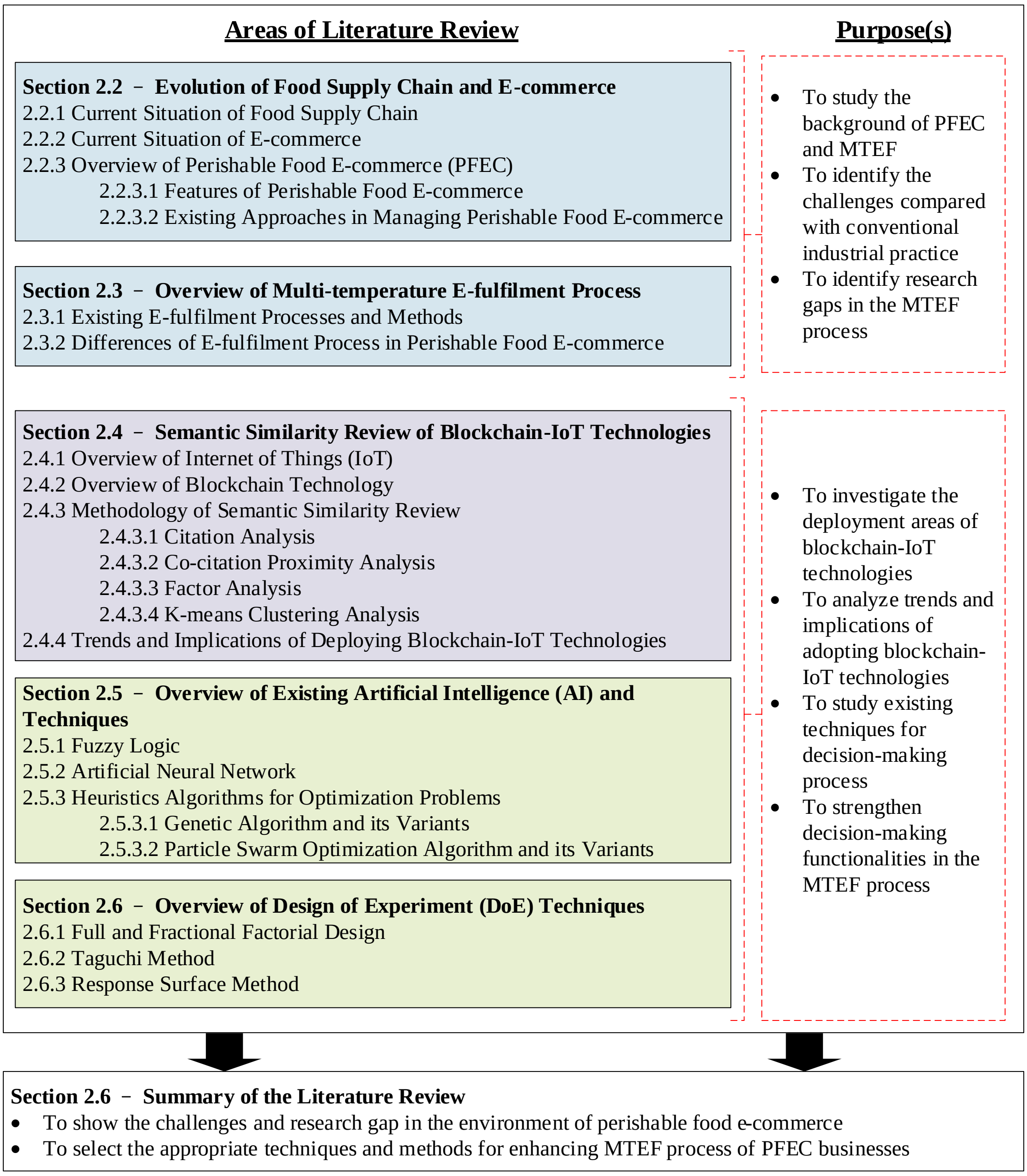


Figure 2.1 Framework of literature review in the research

Particular to blockchain and IoT technologies, a semantic similarity review is conducted to investigate the feasibility of deploying blockchain–IoT technologies. Therefore, the areas, trends, and implications of using blockchain–IoT technologies were studied, so that appropriate methods could be selected to strengthen decision-making functionalities in the MTEF process.

2.2 Evolution of Food Supply Chain and E-commerce

The core idea of supply chain management is to manage upstream and downstream relationships between supply chain parties (such as suppliers and customers), for distributing designated customer value at minimal costs (Christopher, 2016). Further, Mangan and Lalwani (2016) defined supply chain management as managing a network of upstream and downstream organisations while considering relationships and flows of materials, information, and resources. The goals of supply chain management included value creation, efficiency enhancement, and improved customer satisfaction. In the traditional viewpoint, supply chain parties tended to have cost- and value-advantages to be cost and service leaders in the market. Therefore, the concept of value chain was advocated to understand the differentiation between cost behaviour and service in the primary supply chain and support activities (Fredendall and Hill, 2016). According to Mentzer et al. (2001), supply chain activities can be defined in terms of seven aspects: (i) integrated behaviour, (ii) mutual information sharing, (iii) mutually sharing risks and rewards, (iv) cooperation between parties, (v) the same goals and focus of services, (vi) process integration, and (vii) sustainable long-term relationships. The supply chain activities from suppliers to customers should be improved by procurement, technology deployment, human resource management, and company strategies. Moreover, according to Hugos (2018), effective supply chain management should also focus on production, inventory, location, transportation, and information, which can create and add value to services and end customers.

Due to the presence of e-commerce, traditional supply chain management was influenced by the fact that information distribution and sales channels were changed and turned to the Internet (Johnson and Whang, 2002). E-commerce started with online transactions and trading under B2C and B2B modes, to change business models, markets, and consumer behaviour (Laudon and Traver, 2016). Further, e-commerce proposed changing supply chain management in the aspects of operations (e.g., order fulfilment process and logistics requirements), information sharing (e.g., access to demand and supply information), market structure (e.g., customer types and market segmentation) and economics (cost structure and profitability). Moreover, Golicic et al. (2002) revealed that the increase in e-commerce has resulted in an increase of speed of information sharing and connectivity between parties, which has caused higher uncertainty in the entire environment of the supply chain. In addition, the trust in e-commerce was deemed important for understanding, predicting, and controlling the behaviour of e-vendors, e-commerce platforms, and consumers (McKnight et al., 2002; Gefen and Straub, 2004). Therefore, the eco-system of e-commerce business can be strengthened and consolidated by alignment with the goals of supply chain management.

2.2.1 Current Situation of Food Supply Chain

The food supply chain (sometimes called the agri-food supply chain), is a branch of supply chain management for handling agricultural products covering the life cycle from the farm to the table (Marsden et al., 2000; Ahumada and Villalobos, 2009). In the food supply chain network, the supply chain structure covers the range from farmers, food processors, wholesalers, and distributors to end consumers. Apart from the goals of supply chain management, the food supply chain also focuses on food quality and safety. Complexity in the food supply chain is higher than in traditional systems, due to the limited shelf life, environmentally-sensitive characteristics, and price variability. In recent years, the concept of sustainability in the food supply chain has been promoted to eliminate food loss and wastage throughout the entire supply chain (Govindan, 2018). Sustainable development of the food supply chain and relevant business models have been advocated by considering environmental, economic, and social impacts, to gain further benefits to suppliers, consumers, and the community. Food traceability is another critical element in the food supply chain to minimise the number of unsafe and poor-quality food products in the stages of production and distribution (Bosona and Gebresenbet, 2013; Aung and Chang, 2014). Conventional food labelling systems cannot provide the functions of authentication and ensure safety and quality. Therefore, food traceability was developed to improve supply chain management, trace the information of food safety and quality, and differentiate between food products in the market. Moreover, food traceability systems enable the functions of trace-back and trace-forward in supply chain activities, to deal with food scandals and incidents efficiently. Hence, effective food traceability can build trust and increase confidence between supply chain parties in the entire food supply chain. Olsen and Borit (2018) posited that traceability systems have three major components: (i) identification of traceable resources units (TRUs), (ii) documentation of transformations, and (iii) attributes of the TRUs. The TRUs are defined as traceable objects in the supply chain in a trade unit (e.g., a box), logistics unit (e.g., a pallet), or production unit (e.g., a batch) (Kelepouris et al., 2007; Pizzuti et al., 2014). By making use of TRUs, a traceability tree structure can be established to manage the transactions and movements of food products along the supply chain, where the transformation of TRUs and a complex mixture of TRUs can be visualised. Further, the identification of TRUs in industrial applications is associated with machine-readable codes, such as quick response (QR) codes or radio frequency identification (RFID) technology, for connecting between food products and traceability systems (Costa et al., 2013; Badia-

Melis et al., 2015). Accordingly, activities in the food supply chain can be performed and recorded in a systematic and effective manner.

2.2.2 Current Situation of E-commerce

In recent decades, global e-commerce businesses have focused on many business sectors, covering products to be sold and services to be provided. The trade in global and cross-border e-commerce businesses can be conducted in the following four major modes:

(i) Business-to-customer (B2C) e-commerce

B2C e-commerce is defined as serving end customers with products and services, and the transactions are conducted in online platforms (Kumar and Raheja, 2012). Through the B2C platforms, end customers can receive information about products and services to be paid, where the direct relationship between vendors and customers can be built. Compared with conventional distribution channels, the intermediate supply chain parties in B2C e-commerce are declining, while the importance of order fulfilment and last mile delivery are increasing (Van Duin et al., 2016).

(ii) Business-to-business (B2B) e-commerce

Kumar and Raheja (2012) also define B2B e-commerce as transactions made between business organisations though the online platforms, which is an extension of e-procurement. In contrast to B2C e-commerce, the trade in B2B e-commerce can enjoy benefits between businesses and enterprises, such as volume discount and credit payments. Sila (2013) also revealed that the presence of B2B e-commerce was mainly contributable to trust, top management support, network reliability, scalability, and pressure from competitors. Thus, an online channel for conducting B2B transactions was formulated.

(iii) Customer-to-customer (C2C) e-commerce

C2C e-commerce refers to transactions made between customers directly, as represented by online auctions, which provide a platform for exchanging products and services (Wu et al., 2011). Different to B2C e-commerce, C2C e-commerce has the challenges of asymmetric information and anonymity for transactions; therefore, trust and reputation of the C2C platform are of utmost importance to the success of C2C business models.

(iv) Customer-to-business (C2B) e-commerce

Wang et al. (2016) suggested that the business model of C2B e-commerce refers to the concept of online group buying. The sellers can sell a considerable volume of products and services, while the buyers can enjoy volume discounts. Such a business model is beneficial for sellers in predicting demand and reducing marketing costs for their businesses. In this mode, the relationship between buyers and sellers can be formulated into five steps: (i) product selection, (ii) information broadcasting to users, (iii) user preferences, (iv) searching similar products, and (v) offer negotiation to sellers.

Whichever e-commerce modes are adopted in enterprises and businesses, the core focuses of e-commerce are to build a trust relationship and improve the confidence between supply chain stakeholders (Kim and Peterson, 2017; Oliveira et al., 2017). The assurance of trust in e-commerce platforms is beneficial to the mitigation of vulnerabilities in online commercial transactions; hence, customer satisfaction, loyalty, and intention of repeat purchase can be enhanced. Accordingly, online trust is a crucial component for the recent and future development of e-commerce businesses.

2.2.3 Overview of Perishable Food E-commerce (PFEC)

Due to the rapid growth of the food supply chain and global e-commerce businesses, the integration of PFEC is being promoted and followed with commercial interest. Currently, some of the popular e-commerce businesses and platforms have started developing B2C PFEC businesses, for example AmazonFresh (https://www.amazon.com/AmazonFresh) and JD Fresh (https://fresh.jd.com/). However, when handling perishable items in e-commerce, the entire eco-system of e-commerce businesses is changed. O'Keeffe (2001) was the first to highlight the situation of integrating e-commerce and perishable food industries. The supply chain structure was evolved by the increase of PFEC in two aspects: (i) requirements of effective food traceability from farm origin to end customers, and (ii) consolidation of retail and food service firms. The supply chain for PFEC becomes customer-oriented and value-focused, to differentiate with other competitors in the market. Guo et al. (2017) presented a structure for fresh food e-commerce using forward logistics flow, reverse logistics flow, and information flow, as shown in Figure 2.2. It was also reported that fresh agricultural products have become the 4th largest category in Chinese e-commerce businesses since 2013 (Li, 2014). Therefore, due to the possibility of food deterioration within the supply chain, forward and reverse logistics in PFEC have faced critical challenges in the alignment to the goals of supply chain management.

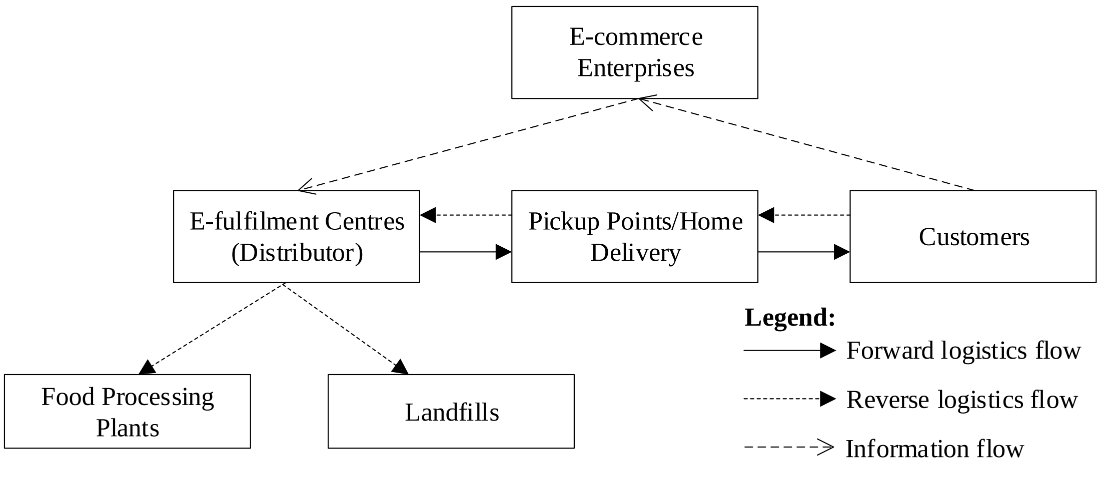


Figure 2.2 Supply chain structure of fresh food e-commerce

Moreover, Zeng et al. (2017) conducted an in-depth systematic review for e-commerce in the agri-food sector regarding the adoption of PFEC in firm- and regional-levels. The factors affecting the adoption of PFEC in firm- and regional-levels were identified, as shown in Table 2.1.

Table 2.1 Factors of PFEC adoption (Zeng et al., 2017)

Groups	**External Factors**	**Internal Factors**
Overall development of PFEC	• Technological changes • Consumers' switch rate • Logistics costs • Accessing international market • Accessing rural areas • Customs fees • Urbanization rate	• Industry structure • Product complexity • Sales channels • Service quality • High-touch nature of transactions • Network effects • Competition among e-market • Cognition and quality of peasants • E-commerce talents • Branding and standardization
Adoption of PFEC by firms	• Industrial contexts • Government • Traction trust and control in supply networks • Market trends • Strategic partners' influence • Competitions	• Market scope • Nature of products or services • Organization structure and culture • Technology competence • Financial commitment • Perceived environment e-readiness • Firm size • Personal traits • Perceived benefits • Follow-up services • Resources availability • Target market segment • Types of business strategy

They also pointed out that the performance of PFEC should be examined by means of systematic approaches in the aspects of online marketing, operations, finance and cross-border market capability. In view of that, the trend of developing PFEC has been proven, and its business value were attractive to the market.

2.2.3.1 Features of Perishable Food E-commerce

With regard to the features of PFEC, it integrates the features of e-commerce businesses and food handling characteristics. First, Leung et al. (2018) indicated that the nature of e-commerce logistics was different to traditional logistics practice in terms of order arrival, order nature, size per order, SKUs, number of orders to be processed, time availability for fulfilment, and delivery schedule. It can be summarised that e-commerce logistics are much more complicated than traditional logistics, as the order volumes are large and fragmented, while the order sizes are relatively small (or even at parcel-level). This results in an increase in the complexity of the order fulfilment process for handling e-commerce orders. Therefore, from the operational perspective, e-commerce logistics are more challenging to industrial practitioners when fulfilling customer expectations. Moreover, Crespo and Del Bosque (2010) summarised three major attributes of e-commerce channels: product perceptions, shopping experience, and customer service. For product perceptions, price, variety, and product quality were determined as the core components for customers to understand and evaluate products in e-commerce platforms. Further, effort, compatibility, and playfulness contributed to the shopping experience, which were required to create the best user experience when visiting e-commerce platforms. Finally, the area of customer service covered the functions of service responsiveness, reliability, tangibility, empathy toward customer needs, and assurance.

Regarding food supply chain features, Rong et al. (2011) reported that complicated food supply chain networks were caused by specific product and process characteristics. To achieve successful of PFEC, food-specific characteristics should be included and considered. First and foremost, food quality is one of the most essential features which should be considered in the PFEC, and maintaining high food quality is dependent on controlling the environmental conditions of storage and transportation facilities. Moreover, food quality can be interpreted to other food attributes, for example integrity, safety, and shelf life. In addition, quality assurance of the food supply chain is also important for creating quality-controlled logistics (Pieter van Donk et al., 2008). Therefore, apart from the typical considerations (such as customer satisfaction and value-added services) in supply chain management, food quality is the key component to be concerned with in the food supply chain. In the world of e-commerce businesses, by merging with the situation of e-commerce logistics, food quality management becomes a challenging task from farmers to end customers. Particularly, the supply chain of PFEC covers last mile delivery of fragmented and small lot-sized orders, instead of only delivering to food retail stores. Therefore, existing food quality management approaches should be enhanced to cater for the requirements in PFEC.

2.2.3.2 Approaches in Managing Perishable Food E-commerce

To manage food products along the supply chain, the literature can be classified into two directions: food production and food distribution. Food characteristics should be considered in these two dimensions to maintain the designated level of food quality to end customers.

(i) Food Production

Managing food products at the production stage effectively is essential to determine the food quality at the beginning. Food sensory evaluation has been a common method to measure human responses to foods, with minimal biasing effect from information influencing customer perception (Lawless and Heymann, 2013). The methods of sensory evaluation can generally be classified into three classes: discrimination, descriptive testing, and affective testing. The discrimination and descriptive classes are analytical measures, and the affective class is perceived as a hedonic measure. In discrimination testing, triangle tests (to select the most different one among all foods), duo-trio tests (to inspect whether the foods match the reference one), and paired comparison (to choose the outstanding one) are three common testing methods (Ennis and Jesionka, 2011). Descriptive evaluation is considered the most comprehensive and informative evaluation tool for food sensory evaluation, and the results can be analysed through statistical techniques. The areas covered in the descriptive evaluation include the surface, first bite, first chew, chew down, and residual of the food products (Richter et al., 2010). Affective testing, which is different to the other two classes, is a hedonic measurement for evaluating customer perspectives and the degree of like or dislike for food products (Chae et al., 2010). It is relatively subjective to the feelings of customers and individual preferences; hence, the sample size with this testing method should be sufficiently large to maintain statistical significance. On the other hand, regarding the perishability and shelf life of food products, the first-expired-first-out (FEFO) management strategy has been proposed to manage the stock in warehouses, rather than applying the first-in-first-out (FIFO) approach (Hertog et al., 2014). The objectives of minimising the amount of food waste and maximising average food quality of products stored in warehouses can be achieved by implementing FEFO.

(ii) Food Distribution

Recently, multi-temperature food distribution (in which the transported food has different recommended handling conditions) has drawn significant attention with regard to issues of food quality and safety among supply chain activities. Almost one-third of produced food is wasted or lost annually due to ineffective management in harvesting, storage, and transportation throughout the entire supply chain (Food and Agriculture Organization, 2017). When importing premium fruit and vegetables with similar food spoilage situations, an extraordinary capital loss can be incurred; hence, suitable attention should be paid to effective food management in distribution. To eliminate food loss and waste in different supply chain elements, there are several international standards for implementing quality assurance systems to ensure food quality and safety throughout the supply chain process. These include good agricultural practice (GAP), good manufacturing practice (GMP), and hazard analysis of critical control points (HACCP) (Amoa-Awua et al., 2007; González-Rodríguez et al., 2011; Baldera Zubeldia et al., 2016). These practices recommended using certain refrigeration systems in trucks and storage areas, while the shortest possible delivery routes should be taken when handling temperature-sensitive food. However, logistics companies may face a challenge between cost-effectiveness and performance in the adoption of certain refrigerated trucks and facilities when ensuring products are handled within prescribed limits. This is because such refrigerated trucks are only available with a fixed set of environmental conditions, and it is difficult to satisfy all handling requirements, particularly in consolidated shipments. Consequently, the ontology of multi-temperature joint distribution (MTJD) has been proposed. Further, certain delivery advancements (including cold cabins and eutectic plates) have been applied to reduce operation costs and improve product quality and safety (Kuo and Chen, 2010). Therefore, the formulation of an appropriate cold chain packaging model is a critical factor in food distribution, and affects the delivery routing. In general, there are three major types of cold chain packaging models: active, passive, and hybrid systems (Ahvenainen, 2003; Kerry et al., 2006; Romero, 2013). Active systems mainly use refrigeration and thermostatic control, passive systems mainly adopt phase change materials, while hybrid systems use phase change materials controlled by a refrigeration system. Table 2.2 shows a comparison of these three cold chain packaging models, in the aspects of pallet size, cost, thermal flexibility, reliability and ease of use. In the MTJD network, the passive cold chain packaging model is preferred to manage products with different recommended transport conditions, due to its low cost and high flexibility for varying thermal conditions and shipment sizes. The reliability of such a passive packaging model can be maintained with a given set of standard operating procedures.

Table 2.2 Comparison of active, passive and hybrid cold chain packaging model

Criteria	Types of cold chain packaging model		
	Active	Passive	Hybrid
Pallet Size	Standard	Customized	Standard
Cost	High	Low	Moderate
Thermal flexibility	Fixed	Flexible	Fixed
Reliability	High	High[a]	Moderate
Ease of use	Easy	Difficult	Moderate

[a] SOP required, and stands for standard operating procedures in cold chain packaging model.

2.3 Overview of Multi-temperature E-fulfilment Process

The order fulfilment process (OFP) has always been an active area in supply chain management to generate, fulfil, deliver, and serve customer orders (Croxton, 2003). Order fulfilment covers all relevant activities to define customer requirements, design the logistics network, and fill customer orders. Forslund (2007) defined OFP activities as including order entry, order processing, order fulfilment, and order delivery, where operational information was exchanged between supply chain parties. In the era of online retail, the OFP refers to all activities, from the point of making an online purchase to the moment of receiving orders by end customers (Nguyen et al., 2018). The performance of OFPs is a determinant and dominant factor in the success of e-commerce businesses. Without this, customer loyalty to e-shops can be negatively affected. Therefore, effective methods and strategies for the design of distribution networks, inventory management, and delivery should be implemented.

2.3.1 Existing E-fulfilment Processes and Methods

Nguyen et al. (2018) proposed an order fulfilment framework, which consisted of three components: (i) inventory management, (ii) last-mile delivery, and (iii) returns management. These three order fulfilment activities were combined with three types of consumer behaviour: (i) purchasing activity, (ii) re-purchasing activity, and (iii) product returning.

(i) Inventory Management

With respect to e-commerce businesses, stock of physical products is kept in fulfilment or distribution centres. Further, the inventory is managed under the specific handling requirements. Different to typical freight forwarding and distribution centres, break-bulk of physical goods is required from pallet- or container-levels to piece-levels for an effective assortment packing process (Gunasekaran et al., 2002). When customers place orders in e-commerce platforms, fulfilment centres can respond quickly to pick and pack customer orders. Therefore, in this section, it is described how inventory management and forecasting and scheduling of the workforce is essential to satisfy the challenging requirements of e-commerce business environments. Rahman and Casanovas (2017) proposed an integrated strategy to predict e-commerce inventory and order planning through estimating online customer demand by using historical sales records. The proposed strategy was integrated in the newsvendor model to provide decision support to the area of inventory management. In addition, warehousing systems in e-commerce have evolved to fulfil the different characteristics of e-commerce warehouses, including small orders, large assortments, tight schedules, and varying workloads (Boysen et al., 2018). They studied the differences and effectiveness of six automated warehousing systems to manage e-commerce inventories: advanced picking workstations, shelf-moving robots, AGV-assisted picking, dynamic order picking, batching, zoning & sorting and mixed-shelf storage. To comprehend e-commerce warehouses, system selection, ergonomics design, and return flows should also be focused on catering to the needs of online retailing.

(ii) Last Mile Delivery

Routing and delivery problems are also active research areas in the OFP of e-commerce business. Different to the traditional vehicle routing problem, routing in OFP should consider several additional factors, such as order delivery time window and various types of vehicles. Deng et al. (2016) presented a closed-loop routing model considering both quality and non-quality defect returns for enhancing the routing capability in e-commerce supply chain systems. Liu et al. (2017) proposed a capacitated vehicle routing problem considering the dynamic order availability time, where the actual order availability time was determined after the completion of order picking and packing. The estimated order availability time used in traditional routing problems did not provide accurate evaluation for formulating the delivery schedule. To cater the changes of routing over the time, Kumar and Panneerselvam (2015) suggested a time-dependent vehicle routing problem with time windows for e-commerce deliveries. The delivery routing had to consider visiting all customers within planned time windows and traffic conditions at different times of the day. Therefore, the fulfilment of customer expectations and orders are more challenging compared to typical vehicle routing problems.

(iii) Return Management

Return management is a less-touched area in e-commerce businesses, as it is the backward and non-profitable logistics process in view of entire supply chain activities. Thus, though it cannot directly gain financial benefits from customers, customer satisfaction, loyalty and profitability can be damaged without proper return policies (Hjort and Lantz, 2016). Bernon et al. (2016) conducted an empirical study to reveal the effect of return rates and policies. To establish the return policies in e-commerce business, products with different levels of quality should be classified for deciding whether they can be returned to stock, such that the return process can be simplified. Further, Chen et al. (2017) proposed a novel way of handling citywide e-commerce reverse flows by using taxis, so that return goods can be handled together with passengers in an integrated manner by leveraging the vehicle loading capacity and mobility. Such an idea made use of sharing economics and crowdsourcing solutions to reduce the economic, environmental, and social impacts of e-commerce return management. Different to inventory management and last mile delivery, return management is not a mandatory and free service to end customers, and reverse logistics is not sufficiently comprehensive at the current stage to cater for the business of global online retailing.

2.3.2 Differences of E-fulfilment in Perishable Food E-commerce

In addition to the above three dimensions of the e-fulfilment process, the order fulfilment process in PFEC is different to typical e-commerce businesses, as the considerations of food perishability and supply chain visibility are required. First, during the supply chain journey, perishable food items can deteriorate, whereby their quality can be affected if the ambient environmental conditions are not well controlled. Accordingly, the complexity and difficulty of inventory management and last mile delivery are increased. As mentioned previously, FEFO is a promising management approach for the inventory of perishable food (Hertog et al., 2014). It should be noted that food products close to expiration dates should be shipped out to customers quickly. In addition, several studies have also attempted to design new inventory policies to cater for the needs when handling perishable food items, where replenishment, delivery, and inventory management should be integrated as a complete process (Bottani et al., 2014; Coelho and Laporte, 2014). Because the quality of perishable food items can vary from time to time, dependent on management policies, the product price can be also affected by its level of quality. In view of this, Herbon et al. (2014) examined the dynamic pricing strategy by considering time-temperature indicators that refer to the evaluation of food quality. Piramuthu and Zhou (2013) also discussed existing inventory systems that incorporate deterioration, which should focus on improving the accuracy of inventory management, resulting in less wastage, higher profitability, and a strengthening of customer satisfaction. Regarding the existing management approaches, there are two major concerns when handling perishable food items: (i) over- and under-estimation of food shelf life, and (ii) different rates of degradation of perishable foodstuffs. These two considerations should also be extended to the e-fulfilment process. On the other hand, the demand of supply chain visibility for perishable food is high in the e-fulfilment process, because PFEC needs to satisfy not only the business organisations, but also end customers. In the past, supply chain visibility was sufficient for handling B2B transactions by effective communication between supply chain parties using advanced technologies, such as wireless sensor networks (WSNs) and RFID technologies (Grunow and Piramuthu, 2013; Piramuthu et al., 2013; Qi et al., 2014). However, for handling B2C transactions, the requirements of supply chain visibility are extended, where the e-commerce orders are fragmented, small in lot size, and high in volume. Simply adopting state-of-the-art technologies is neither sufficient nor cost-effective for achieving supply chain visibility in the entire supply chain network. Therefore, the technology adoption framework should be refined to customise it for PFEC and satisfy customer requirements.

2.4 Semantic Similarity Review of Blockchain-IoT Technologies

To review blockchain and IoT technologies, overviews and descriptions of IoT and blockchain technologies are presented. Subsequently, a semantic similarity review method (co-citation proximity analysis) is adopted to generate several factors and areas that are focused on in the existing literature and work. Consequently, the trends and implications of using blockchain and IoT technologies can be organised systematically so as to support the research and development activities.

2.4.1 Overview of Internet of Things (IoT)

Under the IoT environment, smart objects that integrate wireless communication technologies, sensors, and actuators can connect to the Internet and share their data, to provide real-time data acquisition and management (Wortmann and Flüchter, 2015; Yan et al., 2016). Objects equipped with IoT devices and technologies can be interconnected to achieve specific industrial and daily purposes, such as smart cities, smart health, and smart logistics.

The fundamental architecture of IoT consists of four layers: sensing, gateway/network, management service, and application (Dweekat et al., 2017; Rezaei et al., 2017). The sensing layer covers the physical objects and the deployment of IoT technologies in real-life situations; the network layer refers to the data transmission between IoT devices and IoT development platforms through certain IoT transmission protocols; the management service layer includes performance monitoring and function management in the IoT development platform, to provide stable and reliable application development environments and IoT connection channels; the application layer refers to system development in the selected IoT development platform, including the front-end and back-end developments, and incorporating cloud computing and databases. Compared with RFID technology, IoT is an expanded concept that emerged from the prerequisites of the RFID foundation, to provide object identification and monitoring, evaluation, and interconnection between objects. Apart from developing automatic data capturing technology, an IoT-based system has a structured network infrastructure for connecting both physical and virtual objects, to enhance the capability of data capturing, event transfer, network connectivity, and interoperability.

Wearable technology has been developed to reflect the actual personal health status for further analytics, while several sensors are integrated to collect real-time bio-signals such as heart rate, body/skin temperature, and blood pressure (Pantelopoulos and Bourbakis, 2010). Other sensor technologies, such as temperature sensors, can be applied to build a wireless sensor network in to monitor warehouse environmental conditions (Wu et al., 2015). In recent years, the feasibility of machine-to-machine (M2M) protocols, such as IPv6 over wireless personal area network (6LoWPAN), message queueing telemetry transport (MQTT), and extensible messaging and presence protocol (XMPP), on wireless communication links have been investigated. The sensors in such networks can directly communicate to the Internet, and by doing so, the sensor network can be operated in a scalable and efficient manner with increasing interoperability and standardisation (Higuera and Polo, 2011). Therefore, the presence of IoT technologies can not only to formulate specific business-oriented and industrial solutions, but also improve the whole eco-system of the smart environment effectively. In addition, IoT technologies have a high capability to integrate with other emerging techniques, including blockchain and artificial intelligence, to facilitate digitalisation, automation, and intelligence in daily life.

2.4.2 Overview of Blockchain Technology

The concept of blockchain was firstly initiated by Satoshi Nakamoto in his white paper entitled “Bitcoin: A Peer-To-Peer Electronic Cash System” in 2008 (Nakamoto, 2008). His paper mainly described how the flow of online transactions and a peer-to-peer network between various parties can be completed without involving any financial institutions. Further, blockchain is the key component in achieving trust and consensus in the network. In the traditional public ledger and electronic cash system, centralised financial institutions have the role of managing and balancing cash flow and transaction activities. However, most of the aforementioned services require handling charges paid by the users, and the whole process is not sufficiently transparent. To solve these challenges, cryptocurrency was established to provide secure transactions through using cryptography, and Bitcoin was the first application to realise the above concept. Zheng et al. (2018) summarised that blockchain is constructed in a sequence of blocks, which keep a full list of activity records similar to traditional public ledgers. The beginning block in the blockchain is called the genesis block, and additional blocks are added sequentially after the genesis block. Nofer et al. (2017) identified that blockchain technology is a disruptive technology that influences and triggers changes in various industries, not only when handling online transactions, but also with intermediation and ownership verification. Pilkington (2016) mentioned that the creation of blockchain was able to eliminate the double-spend problem though the adoption of asymmetric encryption in the blockchain technology. Every node in the blockchain network is aware of the activities and transactions. Once a node is validated, the information and data block are publicly announced to all nodes in the network.

In general, there are three types of blockchain: public, consortium, and private (Lin and Liao, 2017; Lai and Chuen, 2018). Fundamentally, public blockchain is open to the public (and anyone who wants to participate in the distributed network), and they create and verify the blocks through an agreed consensus mechanism, for example Ethereum and Bitcoin. Consortium blockchains refer to a partially public distributed network, where some nodes in the network are selected in advance. The data in the blockchain can be open or restricted, which is dependent on the functions and objectives of the consortium blockchain. Finally, in private blockchains, all the nodes are restricted for a particular organisation or company to achieve its goals of using blockchain. Data access and management are strictly controlled by the organisation.

Table 2.3 displays a comparison between these three types of blockchain, from the aspects of data management, vulnerability, efficiency, consensus determination, and data accessibility. Selecting the type of blockchain should strike a balance between their advantages and disadvantages.

Table 2.3 Comparison between public, consortium and private blockchains

	Public blockchain	**Consortium blockchain**	**Private blockchain**
Data management	Decentralized	Partially decentralized	Centralized
Vulnerability	Low	Medium	Medium
Efficiency	Low	High	High
Consensus determination	All nodes	Selected nodes	Privately controlled
Data accessibility	Fully open	Partially open	Restricted

2.4.3 Methodology of Semantic Similarity Review

In the knowledge domain of blockchain and IoT, most of the scholars have studied the background, formulation, and development of the corresponding techniques and mechanisms. Concerning the integration of blockchain and IoT technologies, areas to conduct research and development should be investigated to support the formulation of research directions and focuses. To achieve the above objective, a semantic similarity review approach is applied to investigate the correlation of the groups of research work, instead of simply summarising the existing literature (Shiau, 2016; Ng et al., 2018). The above studies proved the effectiveness of using a semantic similarity review in the fields of enterprise information systems and Internet of Things. Accordingly, the method can be further extended to other promising and emerging research areas. Figure 2.3 presents a schematic diagram of the semantic similarity review approach to be applied in the investigation of blockchain and IoT technologies. Referring to the figure, the data pertaining to existing research were collected from the Web of Science by inputting keywords (i.e., {*blockchain*, *IoT*, *Internet of Things*}). The Web of Science is a well-known and popular research engine, which collects a number of highly reputable scientific research works, including research from the science citation index expanded (SCIE), social sciences citation index (SSCI), and emerging sources citation index (ESCI). Consequently, the quality of the research extracted for analysis can be guaranteed. By using the Web of Science, a total of 308 research works were obtained in the domain of blockchain and IoT technologies on 31st July 2019 (covering articles and conference proceedings) to further conduct the analysis. Subsequently, citation and co-citation proximity analyses were then applied to build the co-citation proximity matrix for evaluating a correlation between the highly influential research work.

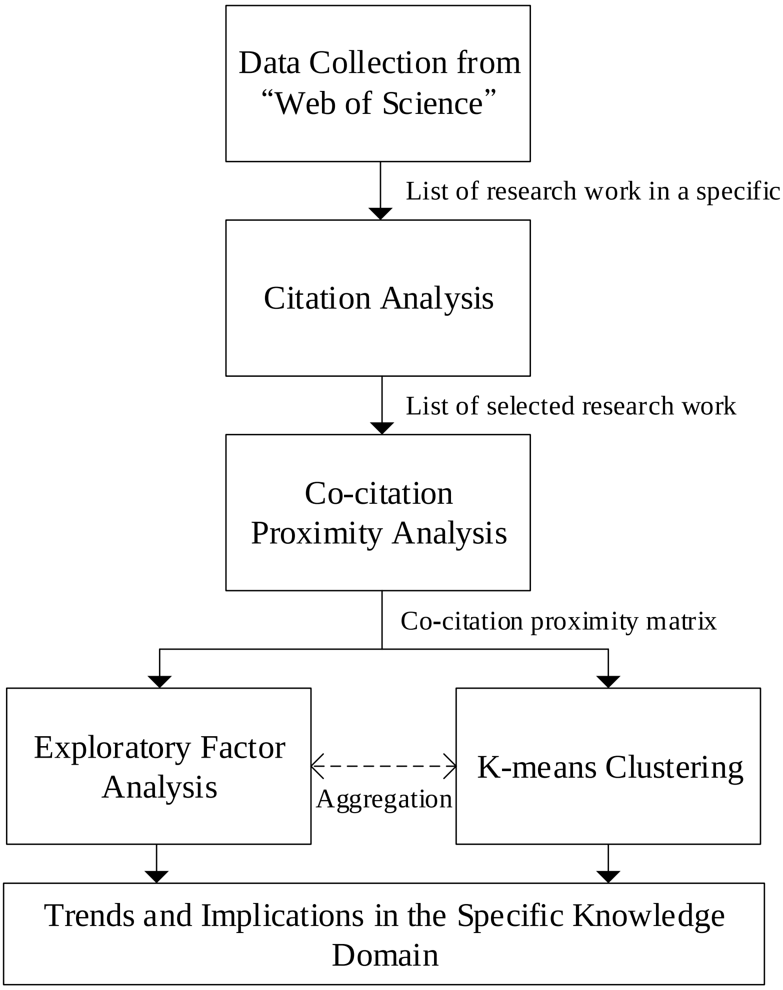


Figure 2.3 Schematic diagram of the semantic similarity review approach

The period of conducting the entire semantic similarity review covered the duration of the research study (until 31st July 2019) for finalising the co-citation proximity matrix for data analytics. In this study, the matrix was continually updated to collect the latest citation status from the Web of Science in the domain of blockchain and IoT technologies. To analyse the trends and implications from the research work, exploratory factor analysis (EFA) and K-means clustering were adopted to categorise the research work, and the results were cross-validated. The aggregation between EFA and K-means clustering was then achieved by combining the similar categories of the research work, in which they have the similar group members in the categories. In return, the resultant groups of research work can be identified; hence, the trends and implications from the domain of blockchain and IoT technologies can be obtained.

2.4.3.1 Citation Analysis

According to Tomcho et al. (2015), the number of citations in research work implies the significance of the work and the explicit links with other research work. Citation analysis refers to the frequency of specific research works that are cited by other authors in their work. A higher number of citations means that more scholars paid attention, and further similar research work is formulated. Therefore, citation index of the research work can be a promising indicator for revealing the impact and influence to a specific field of research. However, only relying on the citation analysis cannot effectively investigate the relationship and links between research work; hence, a co-citation analysis should be further applied. In this review, a threshold of 10 citations of the research work was determined, meaning highly influential articles can be selected. Table 2.4 shows the results of citation analysis for the 34 most frequently cited publications in the domain of blockchain and IoT., according to the data from Web of Science data at 31st July, 2019. As the selected research works had been cited by 10 other research works, correlations between research works can be effectively investigated by using co-citation proximity analysis. Therefore, the relationship between the selected research works can be determined, and similar research works can be grouped and categorised together to formulate the trends and implications from the domain of blockchain and IoT technologies.

2.4.3.2 Co-citation Proximity Analysis

To analyse the correlation between the research articles, co-citation analysis was proposed according to bibliographic coupling (Boyack and Klavans, 2010). The concept of co-citation analysis can also be extended to assess the relationship between topics, authors, journals, and keywords. For example, Wang et al. (2016) developed a semantic similarity review on the area of cloud computing research, by using citation and co-citation analyses to investigate the frequency that two research documents were cited together in the same research documents. Moreover, Ng et al. (2018) applied the same method to conduct citation and co-citation analyses in the area of IoT. The co-citation index was then accumulated to evaluate the closeness of the two research documents.

Table 2.4 The 34 most frequently cited publications of blockchain and IoT

ID	Journal/Conference	Authors	Research Topics
J1	IEEE Access	Christidis and Devetsikiotis, 2016	Blockchains and Smart Contracts for the Internet of Things
J2	2017 IEEE 6th International Congress on Big Data (Bigdata Congress 2017)	Zheng et al., 2017	An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends
J3	2017 19th International Conference on Advanced Communications Technology	Huh et al., 2017	Managing IoT Devices using Blockchain Platform
J4	International Journal of Production Research	Xu et al., 2018	Industry 4.0: state of the art and future trends
J5	IEEE Access	Sharma et al., 2017	A Software Defined Fog Node Based Distributed Blockchain Cloud Architecture for IoT
J6	International Journal of Web and Grid Services	Zheng et al., 2018	Blockchain challenges and opportunities: a survey
J7	IEEE Internet Of Things Journal	Novo, 2018	Blockchain Meets IoT: An Architecture for Scalable Access Management in IoT
J8	Peer-To-Peer Networking and Applications	Zhang and Wen, 2017	The IoT electric business model: Using blockchain technology for the internet of things
J9	Proceedings of 2016 IEEE 18th HPCC/14th SMARTCITY/2nd DSS	Biswas and Muthukkumarasamy, 2016	Securing Smart Cities Using Blockchain Technology
J10	Financial Innovation	Sun et al., 2016	Blockchain-based sharing services: What blockchain technology can contribute to smart cities

Table 2.4 (Continued)

ID	Journal/Conference	Authors	Research Topics
J11	2015 8th International Conference on Intelligence in Next Generation Networks	Zhang and Wen, 2015	An IoT Electric Business Model Based on the Protocol of Bitcoin
J12	Future Generation Computer Systems	Reyna et al., 2018	On blockchain and its integration with loT. Challenges and opportunities
J13	International Journal of Information Management	Kshetri, 2018	1 Blockchain's roles in meeting key supply chain management objectives
J14	Security and Communication Networks	Ouaddah et al., 2016	FairAccess: a new Blockchain-based access control framework for the Internet of Things
J15	Telecommunications Policy	Kshetri, 2017	Blockchain's roles in strengthening cybersecurity and protecting privacy
J16	Journal of Supercomputing	Lee and Lee, 2017	Blockchain-based secure firmware update for embedded devices in an Internet of Things environment
J17	Europe And Mena Cooperation Advances in Information and Communication Technologies	Ouaddah et al., 2017	Towards a Novel Privacy-Preserving Access Control Model Based on Blockchain Technology in IoT
J18	2017 IEEE 24th International Conference on Web Services	Liu et al., 2017	Blockchain based Data Integrity Service Framework for IoT data

Table 2.4 (Continued)

ID	Journal/Conference	Authors	Research Topics
J19	2017 21st International Conference on Control Systems and Computer Science	Stanciu, 2017	Blockchain based distributed control system for Edge Computing
J20	17th IEEE International Conference on Smart Technologies	Karafiloski and Mishev, 2017	Blockchain Solutions for Big Data Challenges A Literature Review
J21	Digital Communications and Networks	Banerjee et al., 2018	A blockchain future for internet of things security: a position paper
J22	2017 IEEE Technology & Engineering Management Society Conference	Ahram et al., 2017	Blockchain Technology Innovations
J23	Computers & Security	Hammi et al., 2018	Bubbles of Trust: A decentralized blockchain-based authentication system for IoT
J24	IEEE Access	Cha et al., 2018	A Blockchain Connected Gateway for BLE-Based Devices in the Internet of Things
J25	2017 IEEE 37th International Conference on Distributed Computing Systems	Shae and Tsai, 2017	On the Design of a Blockchain Platform for Clinical Trial and Precision Medicine
J26	Power and Energy Systems Engineering	Hwang et al., 2017	Energy Prosumer Business Model Using Blockchain System to Ensure Transparency and Safety

Table 2.4 (Continued)

ID	Journal/Conference	Authors	Research Topics
J27	2017 IEEE International Conference on Pervasive Computing and Communications Workshops	Dorri et al., 2017	Blockchain for IoT Security and Privacy: The Case Study of a Smart Home
J28	Journal of Medical Systems	Griggs et al., 2018	Healthcare Blockchain System Using Smart Contracts for Secure Automated Remote Patient Monitoring
J29	2017 2nd IEEE European Symposium on Security and Privacy Workshops	Boudguiga et al., 2017	Towards Better Availability and Accountability for IoT Updates by means of a Blockchain
J30	Future Generation Computer Systems	Sharma and Park, 2018	Blockchain based hybrid network architecture for the smart city
J31	Mathematical Foundations of Computing	Joshi et al., 2018	A Survey on Security and Privacy Issues of Blockchain Technology
J32	Security and Communication Networks	Jesus et al., 2018	A Survey of How to Use Blockchain to Secure Internet of Things and the Stalker Attack
J33	2017 IEEE 1st International Conference on Cognitive Computing	Samaniego and Deters, 2017	Internet of Smart Things - IoST Using Blockchain and CLIPS to make Things Autonomous
J34	Proceedings of the 2016 2nd International Conference on Contemporary Computing and Informatics	Singh and Singh, 2016	Blockchain: Future of Financial and Cyber Security

The co-citation analysis can only show that two research documents are cited simultaneously in another document, meaning the proximity between the two research documents cannot be revealed. Therefore, the co-citation proximity analysis was proposed for further considering the positions of the research documents being cited in another document (Gipp and Beel, 2009). Instead of counting “1” or “0” to represent the correlation of research documents in a traditional co-citation analysis, the co-citation proximity index (CPI) is created to define the occurrence of the research work, as shown in Table 2.5.

Table 2.5 Definition of the value of co-citation proximity index

Occurrence of cited research work	**Value of CPI**
Same sentence	1
Same paragraph	0.5
Same chapter	0.25
Same journal with same edition	0.125
Same journal but different edition	0.0625

The process of co-citation proximity analysis is briefly described as follows: By making use of the publication searching engine (i.e., Web of Science), a set of research documents (excluding review articles) can be obtained to be a set of research documents **R**, which is filtered by using specific keywords. Among set **R**, the highly influential research $\mathbf{R_h}$ can then be sorted by adopting a citation analysis considering the threshold of at least 10 citations in the research documents, where $\mathbf{R_h} \subseteq \mathbf{R}$. Every research document in the set **R** is then checked to determine whether any elements in $\mathbf{R_h}$ occurred in common, and the co-citation proximity matrix can be formulated and updated by referring to Table 2.5. To accumulate the CPI values in the co-citation proximity matrix, the highest CPI value to state the relations between two observing articles is considered (i.e., $CPI_i = \max\{CPI_1, CPI_2, \ldots, CPI_n\}$), where n denotes the number of proximity relations to be located in the observed article. Accordingly, the 34 × 34 co-citation proximity matrix can be formulated in this study to enable conducting factor analysis and K-means clustering.

2.4.3.3 Factor Analysis

After the 34 × 34 co-citation proximity matrix is constructed, factor analysis is applied to group and categorise the highly influential research work to reveal the trends and implication in the knowledge domain of blockchain and IoT technologies. Factor analysis is an approach for modelling covariation among a set of selected variables as a function of one or more latent constructs. There are two types of factor analysis commonly used in covariation evaluation: confirmatory factor analysis (CFA) and EFA (Bandalos and Finney, 2018). The adoption of CFA refers to conducting the analysis with confirmed number of factors, while the EFA does not have the above assumption, such that the number of factors is investigated in the evaluation. In this study, EFA is selected because no prior knowledge with regard to the number of factors was defined. Accordingly, the EFA in this study was conducted using IBM SPSS statistics 22 to analyse the correlation matrix, which was transformed from the co-citation proximity matrix to yield significant factors to the research work. During the analysis, varimax rotation was used to fit the maximal number of documents with the minimal number of factors. According to the screen test, six factors were obtained, explaining 75.863% of the variance in the correlation matrix. Subsequently, the factors were then named based on the summary of the cited research work. Figure 2.4 shows a screen plot, which is a line plot of the eigenvalues of factors obtained from the results of the EFA, so that six major components can be visualised that have an eigenvalue greater than 1. By combining the results from the rotated component matrix, the selected research work in the subset $\mathbf{R_h}$ can be categorised accordingly, together with the corresponding eigenvalue, % of variance explained, and sum of % of variance explained. Therefore, factors 1 to 6 include 23, 2, 3, 3, 1, and 2 selected research works, respectively. Because the majority of the research work was classified into factor 1, this shows that the existing research in the area of blockchain and IoT technologies focuses on one specific construct, and the other five factors are becoming emerging research areas.

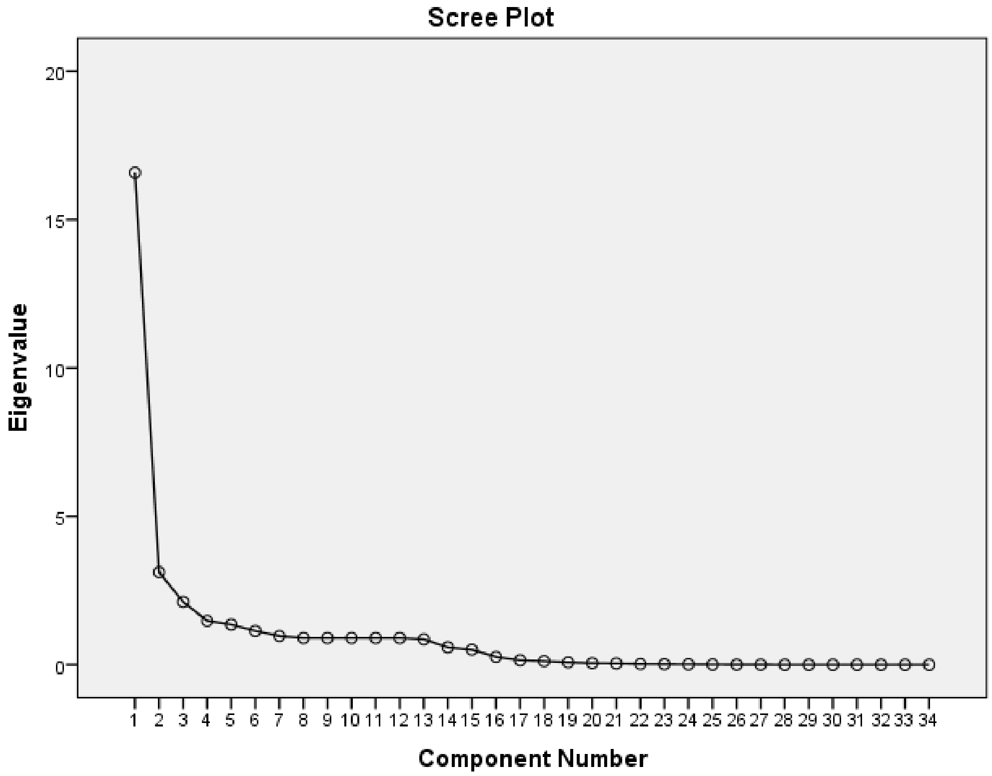


Figure 2.4 Scree plot of the EFA in the semantic similarity review

Through using EFA, six constructs were obtained: (i) frameworks, platforms and challenges of blockchain and IoT technologies, (ii) trust establishment by blockchain and IoT technologies, (iii) Integration of blockchain, IoT and cloud computing for distributed networks, (iv) hardware improvements of applying blockchain in IoT technologies, (v) the innovation process of blockchain, and (vi) application domains of blockchain and IoT technologies. In Table 2.6, the selected research articles were categorized into the six above constructs with showing the corresponding eigenvalue and percentage of variance explained.

Table 2.6 Six factors obtained from the EFA

Factors	Article (#ID)	Eigenvalue	% of variance explained	Sum of % of variance explained
1. Frameworks, platforms and challenges of blockchain and IoT technologies (23 results)	• J1 • J2 • J3 • J6 • J7 • J8 • J9 • J12 • J13 • J14 • J16 • J17 • J18 • J20 • J21 • J23 • J26 • J27 • J29 • J30 • J31 • J32 • J33	16.584	48.777	48.777
2. Trust establishment by blockchain and IoT technologies (2 results)	• J11 • J25	3.121	9.178	57.955
3. Integration of blockchain, IoT and cloud computing for distributed network (3 results)	• J5 • J10 • J19	2.116	6.225	64.180
4. Hardware improvements of applying blockchain in IoT technologies (3 results)	• J4 • J15 • J24	1.479	4.351	68.531
5. Innovation process of blockchain (1 result)	• J22	1.353	3.980	72.511
6. Application domains of blockchain and IoT technologies (2 results)	• J28 • J34	1.140	3.352	75.863

2.4.3.4 K-means Clustering Analysis

To aggregate the results from factor analysis, K-means clustering analysis was applied to classify the research work into the pre-defined number of clusters, which is equal to the number of constructs obtained by using EFA. Clustering analysis is one of the techniques applied in co-citation analysis to categorise the research work, to assist with the interpretation of the statistical findings (Gao et al., 2012; Ding et al., 2014). In K-means clustering, the distances between the research work and cluster centres are computed and minimised. When the change of cluster centres is small and can be neglected, the K-means clustering is then terminated to obtain the clustering results of the research work. By making use of the correlation matrix, the 34 selected articles in this analysis are then assigned to the 6 independent clusters. The K-means clustering analysis was also conducted in the environment of IBM SPSS Statistics 22, and the results are shown in Table 2.7. To interpret the results, the six clusters are named as follows: (i) blockchain development and adoption for real-life situations, (ii) solutions, challenges, and opportunities for blockchain and IoT technologies, (iii) smart contract establishment for industrial applications, (iv) technological development of blockchain and IoT, (v) trust and security for data management, and (vi) models and considerations on the fusion of blockchain and IoT technologies.

Table 2.7 Results of k-means clustering for semantic similarity review

Cluster and its name	No. of members	Article (#ID)
Cluster 1: Blockchain development and adoption for real-life situations	2	• J10 • J19
Cluster 2: Challenges, solutions and opportunities of blockchain and IoT technologies	8	• J12 • J13 • J15 • J20 • J26 • J31 • J33 • J34
Cluster 3: Smart contracts establishment for industrial applications	1	• J28
Cluster 4: Technological development of blockchain and IoT	3	• J4 • J22 • J24
Cluster 5: Trust and security for data management	11	• J1 • J2 • J5 • J6 • J9 • J16 • J17 • J18 • J25 • J29 • J32
Cluster 6: Models and considerations on fusion of blockchain and IoT technologies	9	• J3 • J7 • J8 • J11 • J14 • J21 • J23 • J27 • J30

2.4.4 Trends and Implications of Deploying Blockchain-IoT Technology

From the results obtained by EFA and K-means clustering analysis, some of the categories commonly occur to partition the group of highly influential research work; therefore, they can be combined as the emerging trends of blockchain–IoT technologies. Referring to Tables 2.6 and 2.7, five major categories can be generated by combining the factors obtained by EFA and clusters obtained by K-means clustering analysis: (i) factor 1 and cluster 2, (ii) factor 2, clusters 3 and 5, (iii) factor 3 and cluster 6, (iv) factor 4 and cluster 4, and (v) factor 6 and cluster 1. Regarding factor 5, it only has one single journal, and the clustering analysis cannot explore the relevant research area. It is difficult to draw a summary on factor 5 due to limited evidence and relevant journals at this stage; therefore, the direction from factor 5 is neglected after the data analysis. For the other five categories, the results from EFA and K-means clustering can be aggregated to generate five corresponding trends and implications for deploying blockchain–IoT technologies can be formulated to support the future research work and studies, namely (i) frameworks and platforms of blockchain–IoT technologies, (ii) fusion of blockchain, IoT, and cloud computing, (iii) establishment of trust in the distributed networks, (iv) security and privacy for data sharing and management, and (v) industrial applications of blockchain–IoT technologies. They can also be defined as the current and future research directions in the domain of blockchain–IoT technologies. To express ideas about the results, the above trends and implications are explained and illustrated by summarising the selected research work as follows:

(i) Frameworks and Platforms of Blockchain–IoT Technologies

To adopt blockchain technology and integrate IoT technologies, several scholars proposed specific frameworks, architectures, and even platforms to meet various requirements from industrial applications (Huh et al., 2017; Lee and Lee, 2017; Novo, 2018). Novo (2018) studied the challenges and remedies by means of blockchain and IoT technologies, and an architecture was proposed to support distributed access control and management. The advantages in the areas of mobility, accessibility, concurrency, lightweightness, scalability, and transparency can be added in the existing IoT solutions. In addition, six core components for formulating blockchain–IoT solutions were defined: wireless sensor networks, managers, agent nodes, smart contracts, blockchain networks, and management hubs. Further, Christidis and Devetsikiotis (2016) mentioned three dimensions to conduct blockchain taxonomy: access rights to the network, block creation and mining, and business models. This is to establish distributed peer-to-peer systems for achieving mutual consensus. In addition, consensus algorithms (such as proof of work (PoW) and proof of stake (PoS) in the blockchain) were important to reach consensus among the group of untrustworthy nodes, which is a transformation of the Byzantine Generals Problem (Zheng et al., 2017). The differences between consensus algorithms are measured in terms of node identity management, energy saving, and tolerated power of adversary.

(ii) Fusion of Blockchain, IoT and Cloud Computing

In recent research studies, blockchain technology has been regarded as a disruptive technology in several business models and theoretical foundations of technological development, such as data management and security (Samaniego and Deters, 2017; Sharma et al., 2017). Sharma et al. (2017) adopted blockchain technology to eliminate the challenges in traditional network architectures, for example poor scalability, security, resilience, and low latency. Hence, blockchain cloud architecture for IoT was presented to provide on-demand access and a low-cost environment for industrial applications. In addition, the IoT framework was further enhanced to cover the device, fog, and cloud layers. Reyna et al. (2018) described that there were three major types of blockchain–IoT integration to generalise the practice of blockchain IoT interactions: IoT–IoT, IoT–Blockchain, and a hybrid approach. Undoubtedly, directly using IoT can be the most efficient and effective in terms of latency and security, but a tremendous amount of immutable records is stored in the blockchain. Therefore, cloud computing can be integrated with the blockchain–IoT architecture to achieve hybridisation and allow orchestration. This will enable better management of real-time data delivery and alleviate the negative effects after using blockchain in IoT. Furthermore, the integration of blockchain, IoT, and cloud computing can be effectively formulated by conforming to industrial standards such as IEC 61499 (Stanciu, 2017).

(iii) Establishment of Trust in the Distributed Networks

One of the significant aspects of applying blockchain–IoT is to create trust and consensus among a group of untrustworthy nodes. Further, it is essential for the world of IoT to strengthen its autonomy for data exchange and integrity. Hammi et al. (2018) presented the idea of blockchain adoption to create robust identification and authentication of IoT devices (called bubbles of trust), to avoid malicious use and actions from authorised and unauthorised users of the distributed network. Accordingly, security requirements and threat models have been suggested during blockchain–IoT development to outline the safety and trustworthiness after implementation of blockchain. In a distributed network, nodes do not need to trust each other, but have to build a mutual agreed consensus algorithm and attacker model to secure data exchange and improve data reliability (Boudguiga et al., 2017). In addition, making use of smart contracts and the Ethereum protocol can establish automated data retrieval and modification, which are activated through wireless sensor networks. Thus, due to immutability in the blockchain, traceability and transparency of data and transactions can be enhanced, and the establishment of trust when handling sensitive data (such as patient data) can be effectively achieved (Griggs et al., 2018). Accordingly, further innovation and development of blockchain technology can incorporate this advantage.

(iv) Security and Privacy for Data Sharing and Management

Apart from building trust in industrial scenarios, using blockchain can be beneficial with regard to the issues of security and privacy for data sharing and management within the distributed network. Dorri et al. (2017) presented the use of blockchain to strengthen IoT security and privacy in smart home applications, where five major security requirements were considered and achieved: confidentiality, integrity, availability, user control, and authorisation. With the adoption of blockchain in IoT applications, two critical security attacks—including distributed denial of service and linking attacks—can be eliminated. Banerjee et al. (2018) investigated the value of security and privacy concerns in the blockchain for IoT. To maintain privacy concerns and regulations in IoT, the reference integrity matrix (RIM) was proposed to centralise dataset management and to share associated reference numbers for building the data chain. As one of the blockchain characteristics is to distribute the same dataset in the whole network, it might cause risks when handling private and personal information. Therefore, the invention of the RIM and integration with centralised data management (such as cloud computing) is significant to blockchain research. Together with immutability and decentralisation of shared data in the network, security and privacy of dataset sharing can be effectively ensured, and a 51% majority attack of the blockchain becomes extremely difficult to achieve.

(v) Industrial Applications of Blockchain-IoT Technologies

Blockchain was invented for cryptocurrency and financial applications (such as Bitcoin) to eliminate the middleman and intermediate parties for improving the effectiveness of financial transactions (Zhang and Wen, 2015). Apart from typical applications, blockchain technology integrated with IoT can be extended to other industries, such as healthcare and supply chain management. Boudguiga et al. (2017) summarised that blockchain–IoT can generally be applied to smart homes, smart grids, intelligent transport systems, and industry 4.0, which involves complex systems with numerous IoT objects to connect manufacturers in the real world effectively. Shae and Tsai (2017) applied the concept of blockchain for clinical trials and precision medicine to facilitate big data analytics, data management, identity management, and trust data sharing management. Cha et al. (2018) integrated blockchain technology with IoT devices to formulate an improved gateway for data transmission to enhance secure management and access control. Blockchain connected gateways have played a significant role as mediators between users and IoT devices to strengthen privacy and access control. Accordingly, blockchain–IoT technology can be used to support effective data management and trust establishment, while reliable data collection in blockchain ensures the effectiveness of data analytics and evaluation processes.

2.5 Overview of Existing Artificial Intelligence (AI) Techniques

To provide adequate decision-support functionalities for MTEF, artificial intelligence (AI) and experimental techniques are considered in this research. AI is used to mimic the characteristics of human responses and behaviour for problem-solving and analysis (Ali et al., 2015). The application areas of AI cover modelling, optimization, forecasting, system control and selection (Mellit, 2009). Furthermore, the applied AI in several industrial situations can support the decision-making purposes which aim at improving the operational effectiveness and efficiency. Therefore, in this sub-section, fuzzy logic, artificial neural network and heuristics algorithms, including genetic algorithm and particle swarm optimization algorithm, are discussed accordingly.

2.5.1 Fuzzy Logic

Fuzzy logic is a promising AI technique for generating acceptable reasoning with uncertainty and vagueness by mimicking human thinking and decision-making processes (McNeill and Thro, 2014). The crisp sets and linguistic information can be processed by the fuzzy sets with defined membership functions in a decision science approach. In general, the mechanism of fuzzy logic consists of fuzzification, inference engine and de-fuzzification, where the inference engine is connected to the dedicated knowledge repository. Fuzzy set theory was applied to assess the shelf life of fried potato wedges by ranking metal oxide gas sensors as electronic noses (Chatterjee et al., 2014). The signal noise response scale can be fuzzified, and aggregated to an integrated fuzzy variable. In addition, the sensory quality can be examined by using fuzzy logic, where color, flavor, homogeneity, and taste can be ranked systematically (Routray and Mishra, 2012). Furthermore, fuzzy set theory and fuzzy logic have the capability of integrating with other techniques in artificial intelligence and data mining, such as association rule mining and analytic hierarchy process, and are able to integrate with other methods and algorithms to establish fuzzy decision support systems so as to enhance system adaptability and feasibility. The performance of such integrated methods in real-life applications have been well proven (Arafah and Mukhlash, 2015; Lee et al., 2015). However, there are limited studies for integrating the fuzzy logic approach and shelf life assessment model so as to evaluate the shelf life and quality degradation rate. Therefore, the customization of shelf life management to food products can be established by integrating sensory evaluation and handling conditions in the whole supply chain through the use of fuzzy logic.

Therefore, the applications of fuzzy logic can be an addition and extension to the food shelf life management in order to establish dynamic and customized shelf life and quality decay model.

2.5.2 Artificial Neural Network

Artificial neural network (ANN) is another section in the area of artificial intelligence, which is capable of handling non-linear function estimation, data sorting, optimization, clustering and patter detection (Yadav and Chandel, 2014). The entire process of ANN consists of five components, namely (i) input later, (ii) output layer, (iii) connection weight and biases, (iv) activation function, and (v) summation node. By making use of the above five components, ANN can perform generalization and recalling after sufficient learning and training. Regarding the areas of food quality, ANN is widely applied to evaluate the shelf life of various types of food. Goyal and Goyal (2011) presented an ANN model to predict the shelf life of Kalakand which is an Indian food stored at 6°C, where the prediction was validated by using mean square error, root mean square error and r-square measures. Meng et al. (2012) proposed an ANN model based on a back-propagation algorithm to predict the storage quality of fresh-cut green peppers in the aspects of degree of yellowness, water loss, textual firmness and vitamin C content. Also, temperature, relative humidity, level of carbon dioxide and oxygen were considered to formulate the prediction of shelf life. Alden et al. (2019) also applied ANN and image processing to evaluate the food quality and shelf life of cauliflower with four types of packaging. By using different packaging design, the shelf life can be various even though the products are stored in constant environmental conditions. Therefore, ANN is a promising technique to evaluate the food quality aspects and shelf life by considering deterministic and concrete factors, and the accuracy of the prediction can be guaranteed after conducting sufficient training.

2.5.3 Heuristics Algorithms for Optimization Problems

Differing to exact algorithms, heuristics algorithms are developed to solve the non-polynomial (NP)-hard problems with limited resources and time, such as vehicle routing problem (VRP) and deployment of WSN (Archetti et al., 2011; Tsang et al., 2019a). In this sub-sections, two heuristics algorithms, namely genetic algorithm and particle swarm optimization algorithm, are discussed.

2.5.3.1 Genetic Algorithm and its Variants

According to Kumar et al. (2010), genetic algorithm (GA) is a probabilistic search method based on the mechanism of natural selection and genetic engineering. In genetic algorithms, the solutions are presented in the form of chromosomes or individual representations. Chromosomes can then be evaluated to obtain the corresponding fitness values. The fundamental genetic algorithm involves four major stages: initialization, selection, reproduction and termination. The mathematical modelling should be initialized to formulate a certain number of populations at the beginning. Afterwards, the parent pool and mating pool can be formulated for conducting genetic operations, covering crossover and mutation operations. Thus, the offspring population can then be formulated for forming a group of solutions. To terminate the algorithm, a set of termination criteria should be reached, such as meeting the maximum number of iterations and the threshold of the percentage improvement of solutions. Vidal et al. (2012) described the solution of the multi-depot and periodic vehicle routing problems by the genetic algorithm approach, which showed that the genetic algorithm was well-developed to deal with such problems. Ferentinos and Tsiligiridis (2007) also mentioned that adaptive sensor network design and energy management can be improved though the consideration of multi-objective optimization, solved by genetic algorithm. Apart from the typical genetic algorithm, Deb et al. (2002) proposed a well-known version of an improved genetic algorithm, namely the non-dominated sorting genetic algorithm II (NSGA-II). The sharing parameters in the NSGA-II can be neglected so that the computational complexity and elitism can be eliminated. In return, the pareto-solution of specific problems can be obtained, where the pareto-optimal front can be established to investigate the spread of solutions. The solution convergence and solution quality are better than the traditional genetic algorithms in solving the multi-objective optimization problems.

2.5.3.2 Particle Swarm Optimization Algorithm and its Variants

The particle swarm optimization algorithm is another heuristic optimization method based on swarm intelligence, which was inspired by bird and fish flock movement behavior (Bai, 2010). In the algorithm, the solution swarm moves to search and develop a new solution swarm, considering the better obtainment of information and resources. To solve optimization problems, a number of particles in the swarm are initialized in a multi-dimensional space with its own potential solution. The change of particle is according to three criteria, namely (i) to keep the inertia, (ii) to change the condition based on its optimist position, and (iii) to change the condition based on the swarm's optimist position. Due to its simplicity in formulating particles, the algorithm is a good fit in solving the complex optimization problems, such as model classification, signal processing and system control (Korürek and Doğan, 2010; Gozde and Taplamacioglu, 2011; Xue et al., 2012;). Regarding the applications of the algorithm, the algorithm has been improved and modified by integrating with other AI and optimization techniques (Valdez et al., 2011; Ishaque et al., 2012). Therefore, the algorithm can deal with complex optimization problems having multi-objectives consideration, dynamic optimization environment and discrete solution space. Compared with the genetic algorithm, the particle swarm optimization algorithm has no systematical computation process and well-defined mathematic foundation, so that the solution convergence and robustness are still being investigated.

2.6 Overview of Design of Experiment (DoE) Techniques

DoE is a systematic process to discover the significant impact between inputs and process outputs through conducting certain experiments (Oehlert, 2010; Montgomery, 2017). Experimental techniques are used to solve the problems by attempting various parameter settings and situations so as to evaluate the problem characteristics (Taylor et al., 2012). Experiments consist of four major components: treatment, units, responses, and specific experimental design, without which the relationship and formula between inputs and outputs are difficult to establish. Since the relationship between responses and independent variables are uncertain, several analytical tools are used in investigating the tendencies, measurement errors, and result validation, such as the evaluation of signal-to-noise (S/N) ratios.

2.6.1 Screening Design of Experiment

Screening design of experiment is the first step in the entire process of conducting experiments. Since the number of factors and considerations can influence the process quality and responses, the critical and important factors should be identified before the commence of experiments in order to ensure the effectiveness and efficiency of the experiments (Campolongo et al., 2007). There are three typical methods for the screening design, namely 2-level fractional factorial design, Plackett-Burman design and definitive screening design, which differ in the areas of the maximum number of factors to be considered, levels of considered factors, and screening term properties. In practice, a number of incremental ratios, namely elementary effects, is evaluated so as to measure the average effect of the factors to the design model. In addition, definitive screening design is more capable of assessing both the linear and quadratic effects of parameters (Libbrecht et al., 2015). Therefore, the critical parameters and factors in the experimental design model can be located for effective post data analysis and model optimization.

2.6.2 Full and Fractional Factorial Design

Full and fractional factorial design is commonly used in the experimental design, where the factors are at 2-levels and 3-levels (Antony, 2014). The factorial design is used to investigate the responses from the effect of the factors, including the process factors and design parameters. The full factorial design of experiments indicates that all the possible combinations of the levels of factors are considered, where the total number of experiments for investigating k factors at the 2-levels is 2^k (Das and Dewanjee, 2018). Also, the full factorial design is particularly useful in the stage of preliminary studies, and the number of parameters and factors are less than four. On the other hand, fractional factorial design refers to the selection of a subset of the whole experiment, due to the limited resources and the large number of factors considered in the experiments. The main effects and 2-way interactions are compounded and cannot be independent of the effects of other higher-order interactions (Jaynes et al., 2013).

2.6.3 Taguchi Method

The Taguchi method in DoE, which was a robust design for product and production development processes, is used to examine the optimal factors in the experiment settings with improved performance, quality and cost (Yang and Tarng, 1998; Aveiro, 2016). In the Taguchi method, there are three major evaluations of signal-to-noise ratios, namely (i) larger-the-better (LTB), (ii) smaller-the-better (STB), and (iii) nominal-the-better (NTB). By doing so, the effect of the noise factors can be minimized, and the optimal control factors can be determined. In addition, when optimizing multiple responses in the design models, the multi-response Taguchi method was developed and adopted (Tong et al., 1997; Sahu and Pai, 2015). Subsequently, the contradictory objectives can be modelled in one experimental design, while the interactions can be optimized accordingly. Such applicable methods have also been widely applied in the logistics and supply chain aspect, including selection of third-party logistics service providers, evaluation of proposed Tabu search-based heuristic method in reverse logistics network, and determination of critical control factors in electronic packaging (Eskandarpour et al., 2014; Sharma and Kumar, 2015; Huang et al., 2016). However, there has been limited experimental research on the passive cold chain packaging model, and thus the formulation of an optimal packaging model would be more valuable and beneficial to vehicle routing in multi-temperature food distribution.

2.6.4 Response Surface Method

The response surface method is used to evaluate the interaction and quadratic effects after the important factors are identified using screening or factorial designs, and thus the responses in the model can be optimized (Li et al., 2016). The difference between the response surface method and typical factorial design is consideration of the squared or quadratic characteristics which formulate the curvature in the responses.

Consequently, the response surface method is particularly useful in mapping the response surface region, investigating level of variables for response optimization, and fulfilling the requirements on operating conditions. Central composite design and Box-Behnken design are two major types of response surface models (Zolgharnein, 2013). The former, namely central composite design, can be classified as a factorial or fractional factorial design with the center point and a group of axial points, and thus the curvature of the model can be measured. Also, it is effective to investigate the first and second order terms in the experimental models, and to consider the addition center point and axial points in the completed factorial design. The latter, namely the Box-Behnken design, is a kind of response surface method, not having a pre-defined factorial or fractional factorial design. It is used to investigate the first and second order coefficients in the design model.

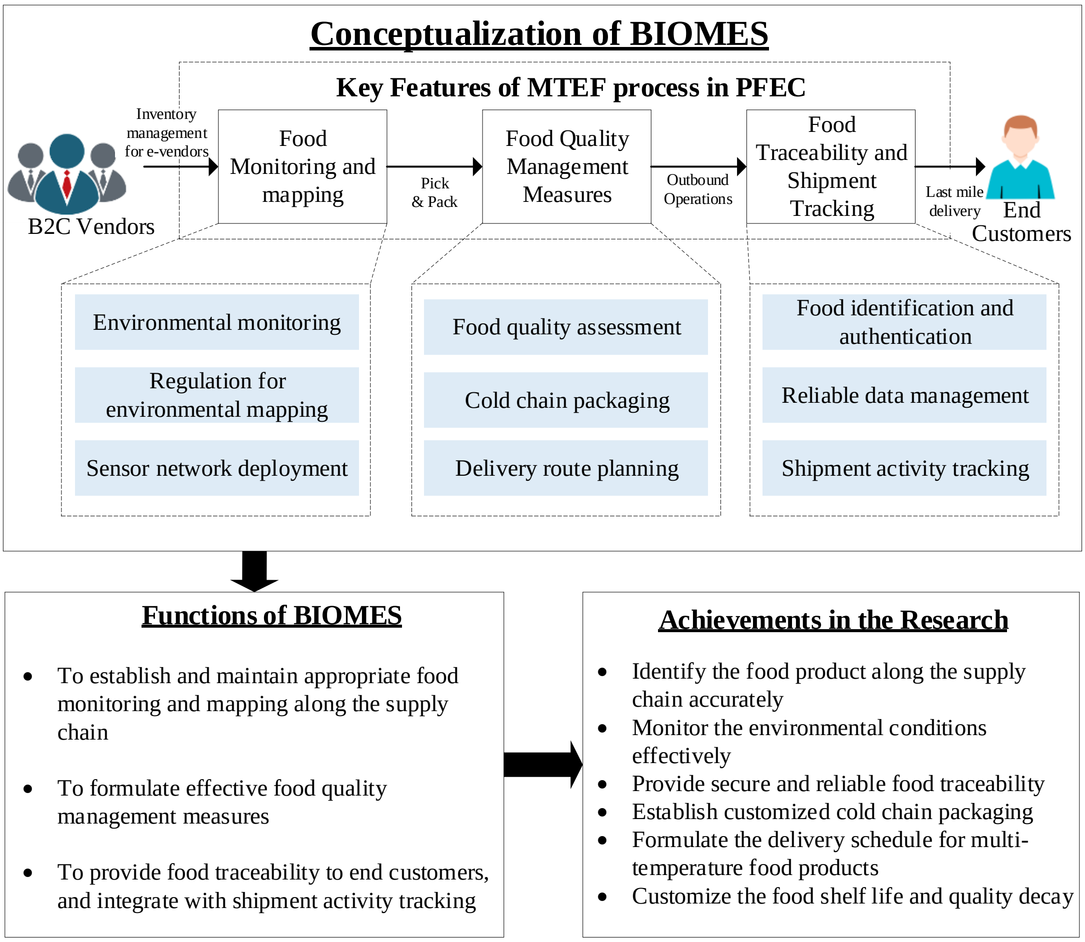
2.7 Summary of the Literature Review

In this chapter, existing literature in the areas of supply chain management and emerging technologies have been reviewed in detail. Due to the growth of e-commerce businesses in the food supply chain, a new business model has appeared in the real world called PFEC. The presence of PFEC derives the MTEF process, which is an improved e-fulfilment process catering for business and customer needs when selling and purchasing perishable foods within the e-commerce environment. It was found that several differences and challenges can be predicted when handling perishable foods by using the existing e-fulfilment process, including data acquisition, food traceability, and food quality management practices. Accordingly, several emerging engineering techniques, including blockchain, IoT, heuristics algorithms, artificial intelligence, and experimental techniques, were studied to establish an effective solution to eliminate the challenges in the MTEF process. Particularly for the advanced topics of blockchain–IoT technology, the semantic similarity review approach was adopted to analyse and categorise the trends and implications of the technology. Consequently, making use of the knowledge in the above technical aspects, the MTEF process can be improved in terms of real-time data acquisition, food traceability, and food quality management. This will strengthen customer confidence and satisfaction when purchasing perishable foods on e-commerce platforms, and improve operational effectiveness and efficiency throughout the entire order fulfilment process. Therefore, the eco-system and atmosphere of PFEC can be further enhanced through the proposed blockchain-enabled IoT system outlined in the next chapter.

Chapter 3. Blockchain–IoT–based Multi-temperature E-fulfilment System

3.1 Introduction

In this chapter, the design of the blockchain–IoT–based multi-temperature e-fulfilment system (BIOMES) is proposed for supporting e-fulfilment processes when handling multiple SKUs of environmentally-sensitive products. The proposed system is developed to fill the research gaps from the presence and unique features of MTEF process in the PFEC, instead of traditional B2C e-commerce services. Figure 3.1 shows the conceptualization of the proposed system, i.e. BIOMES. The design of BIOMES is to solve the existing challenges in the MTEF processes of PFEC, and there are three major areas to be considered, namely (i) food monitoring and mapping, (ii) food quality management measures, and (iii) food traceability and shipment tracking. Followed by product specifications, such as the requirement of handling conditions, the environment of storage areas should be monitored and mapped by complying to international regulations, and the sensor network is then deployed to monitor the environmental conditions. When picking and packing e-orders, customized cold chain packaging should be applied to ensure that ambient environmental conditions are within the specifications, and the maximum time allowed for transportation is determined for supporting the delivery route planning. All the operational and product information is then managed in a secure and reliable manner for the access of e-commerce customers so as to make the shipment status, food information and quality level more visible and transparent.



Functions of BIOMES

- To establish and maintain appropriate food monitoring and mapping along the supply chain
- To formulate effective food quality management measures
- To provide food traceability to end customers, and integrate with shipment activity tracking

Achievements in the Research

- Identify the food product along the supply chain accurately
- Monitor the environmental conditions effectively
- Provide secure and reliable food traceability
- Establish customized cold chain packaging
- Formulate the delivery schedule for multi-temperature food products
- Customize the food shelf life and quality decay

Figure 3.1 Conceptualization of the BIOMES

Therefore, the proposed system improves the business environment and MTEF process of PFEC by satisfying additional customers' requirements. Also, food products are safely and securely handled by providing environmental excursion management and the appropriate measures of food quality management. The eco-system of PFEC can then be established and managed in a systematic and intelligent manner.

3.2 Architecture of BIOMES

The architecture of the BIOMES is presented in Figure 3.2. It consists of three modules, (i) IoT deployment module (IoTDM), (ii) blockchain-enabled data management module (BDMM), and (iii) food quality management module (FQMM). The design of the system architecture is followed the theories of system modelling and layers of IoT systems (Lin et al., 2017; Gao et al., 2019). To achieve desired applications in the PFEC environment, the considerations of physical resources, data acquisition, network communication, data management and decision-making solutions are essential. In view of the layered architecture of IoT systems, there are three to five layers in general, depended on system requirements and specifications, namely (i) perception, network, and application layers, (ii) perception, support, network, and application layers, and (iii) perception, transport, processing, application and business layers. Data in real-life situations can be effectively collected, transmitted and processed to build smart applications for designated business purposes. Consequently, the proposed system, namely BIOMES, in this study follows the above mechanism to structure the data acquisition in IoTDM, data management in BDDM, and applications for improving PFEC and MTEF in FQMM. In the IoTDM, IoT technologies are deployed in an optimal manner, where appropriate technologies are selected according to various TRUs so as to identify products and monitor environmental conditions along the supply chain. In the BDMM, blockchain technology is applied to securely manage the key traceability information and shipment activities for improving supply chain visibility to all stakeholders. The IoT and blockchain technologies are integrated to provide real-time information management for monitoring purposes, and to maintain system synchronization to supply chain stakeholders for food traceability. In the FQMM, the measures of quality management in the MTEF process are enhanced by three proposed areas, namely cold chain packaging, delivery route planning and fuzzy food quality evaluation. Therefore, the proposed system aims at enhancing the e-fulfilment process when handling multi-temperature food products so as to provide an integrated approach for monitoring, traceability and quality management. To ensure the completeness of the proposed system, requirements and documentations from the stakeholders related to performance, environmental and other non-functional concerns are examined in a regular basis (Konnov et al., 2017). Therefore, the system completeness can be guaranteed to fill the identified research gaps and to solve the industrial challenges in the PFEC and MTEF environment.

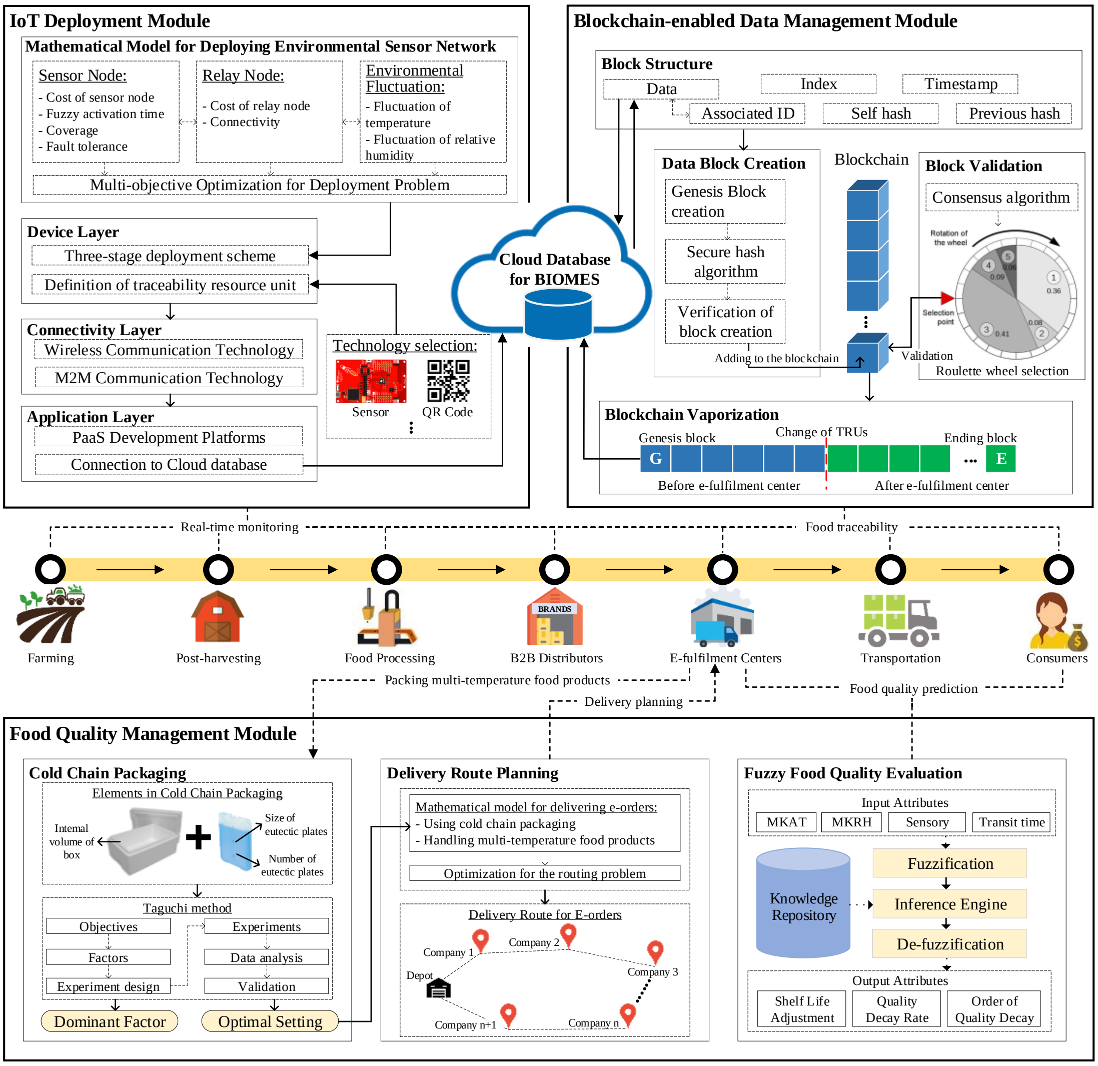


Figure 3.2 System architecture of BIOMES

3.3 IoT Deployment Module (IoTDM)

In this module, IoT technologies are adopted in the supply chain for operating PFEC in order to collect data on real-time environmental monitoring, and in identifying food products. Along the supply chain, the TRUs of the products can be changed, such as batch-level and item-level, so that appropriate technologies should be selected and assigned to achieve the planned objectives. In addition, to maintain the designated environmental conditions in storage areas, an optimized deployment scheme is then presented to address the needs for environmental mapping.

3.3.1 IoT Deployment Framework

To develop a real-time monitoring application for measuring environmental conditions, an IoT framework, which is a standardized structure, is suggested. In general, the IoT framework consists of three major layers, namely perception layer, network layer and service layer (Lin et al., 2017). The perception layer includes the adoption of wireless communication technologies and wireless sensor networks to track and identify objects. The network layer supports the data transmission between physical devices to the host computers. The service layer, also called the application layer, is to develop the proposed solutions and to maintain services and resources effectively. Figure 3.3 shows the proposed IoT framework in this project for the proposed BIOMES. The selection and implementation of IoT technologies need to align with the proposed framework. To build a wireless sensor network for environmental monitoring, SensorTags, CC2650 and CC3200, which transmit the data through Bluetooth/ IPv6 over low power wireless personal area network (6LoWPAN) and Wi-Fi, respectively, are suitable due to the ease of use and economical deployment. The environmental data, including ambient/IR temperature, relative humidity, light intensity and pressure can be captured. The collected data can then be transmitted to the IBM Cloud via the IBM device registration services and MQTT. The Internet of Things platform in IBM Cloud can then be used to develop the system under the Node-red programming environment. The collected data payload is transmitted in the form of JavaScript object notation (JSON), compatible to most of the cloud database structures. Also, such a Platform as a Service (PaaS) platform provides middleware, resource management and sharing technology to support customized system development.

3.3.2 Technology Adoption based on TRUs

Apart from introducing the IoT technologies, the adoption of the technologies should be based on the status of TRUs to define the precision of identification and monitoring, such as batch-level or item-level. During the entire supply chain for operating PFEC, three general TRUs are introduced, namely container-level, batch-level and piece level. In different TRU levels, the various functions obtained from the deployed IoT technologies are required to maintain the designated level of food quality and supply chain effectiveness. At the container-level, food products are handled by using active cold chain containers to ensure that the handling requirements are met. Also, the products are stored in large chilled or temperature-controlled areas so that environmental monitoring and mapping are needed. To facilitate the IoT technology adoption at the container-level, optimization between deployment cost and mapping effectiveness should be considered, resulting in better economic advantages in deployment of wireless sensor networks. At the batch-level, sensors are installed for palletization of the food products so as to monitor the environmental conditions of batches of food products, and the pallets of food are distributed by road transportation between the food processors and distribution centers. Advantages in cost-effectiveness and flexibility for handling food products at the shipment-lot level can be obtained. At the piece-level, after the food products are ordered by end customers in the e-commerce platforms, passive cold chain packaging is applied to minimize the effects from the surrounding environmental conditions to the food products during the order fulfilment process. Moreover, the use of quick response (QR) containing food information, such as name, list of ingredients, source of origin can be used and further improve the transparency of the food product orders. The balance between cost, environmental impact and technology adoption can be made. In addition, the QR codes placed in the outer packaging of the parcels are also connected and associated with the customized food quality assessment, namely environmental monitoring, shelf life and quality decay, and thus the supply chain traceability and visibility can be enhanced.

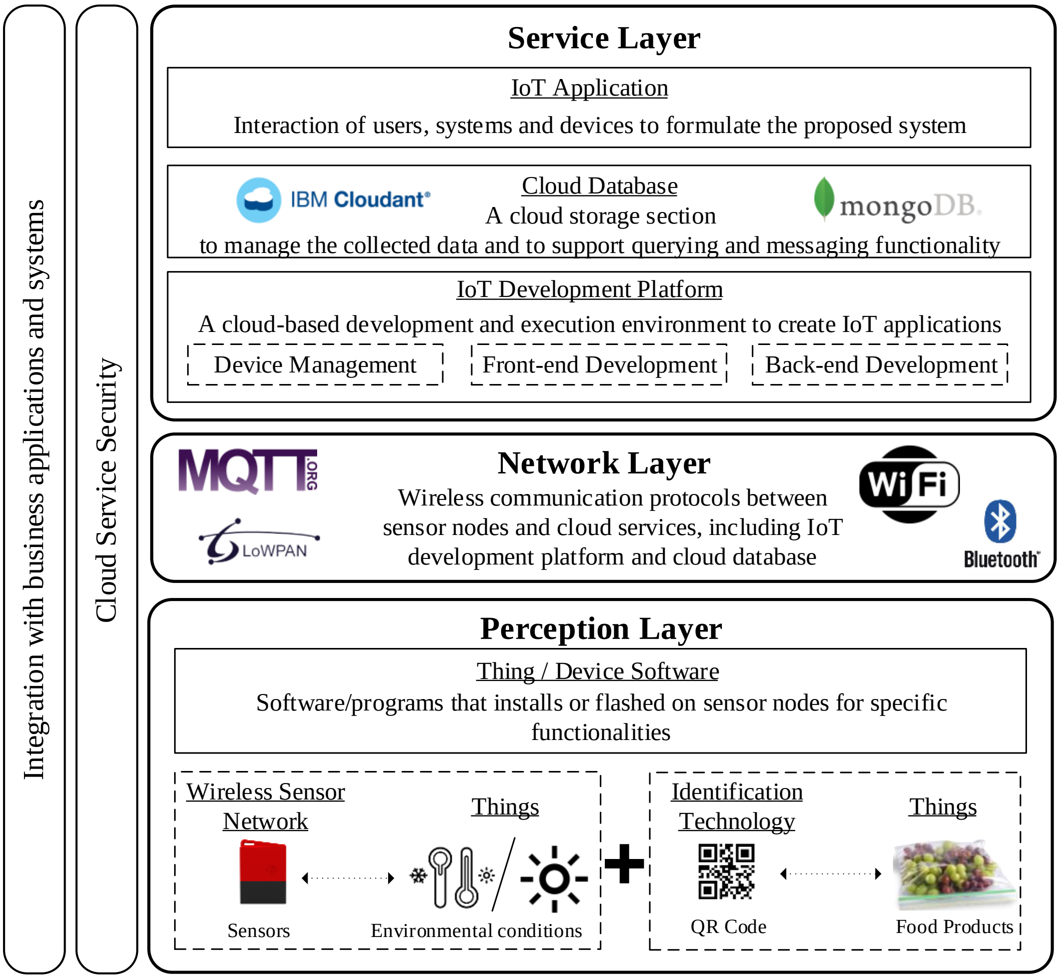


Figure 3.3 IoT framework for BIOMES development

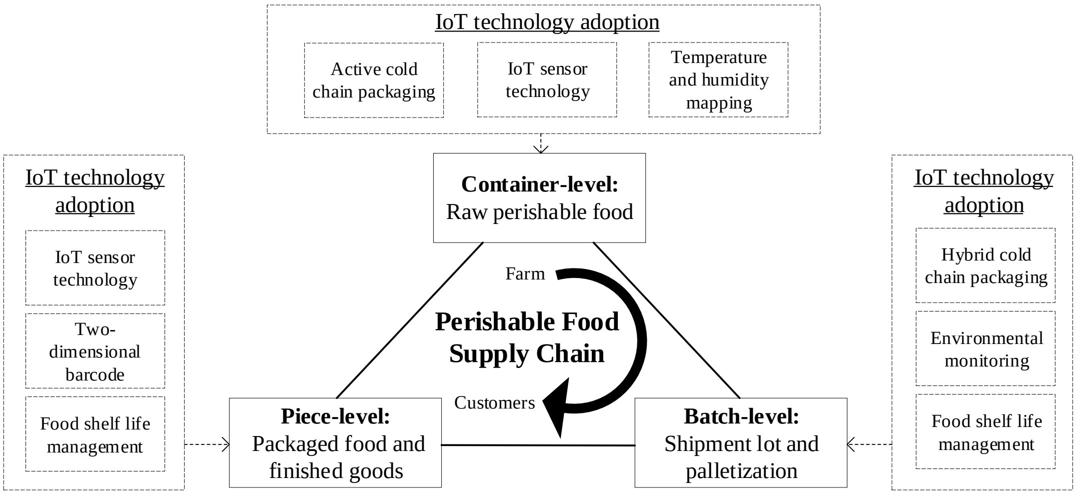


Figure 3.4 IoT technology adoption for different TRUs

3.3.3 Deployment Scheme of Environmental Sensor Network

The deployment scheme of the QR code and attached sensors to batches of food products is trivial and can be referred to typical IoT deployment methods (Badia-Melis et al., 2018). In the storage areas, the indoor deployment of an environmental sensor network (ESN) is needed to comply with the requirements for environmental mapping. In this section, a three-stage ESN deployment scheme is presented, considering six essential factors, namely cost, coverage, connectivity, fault tolerance, airflow and system lifetime (Tsang et al., 2019a). The ESN is implemented in a 3D environment under a Cartesian coordinate system of width (W), length (L) and height (H), as shown in Figure 3.5. Also, the entire 3D environment is divided into three levels, i.e. low level, medium level and high level.

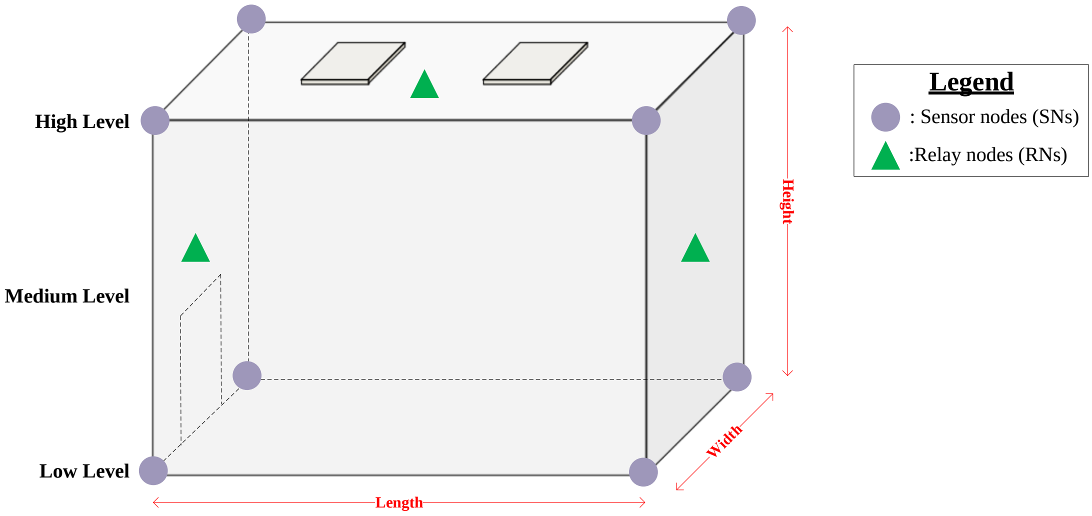


Figure 3.5 Graphical illustration of 3D environment for ESN deployment

3.3.3.1 Stage 1: Sensor Node Deployment

In the first stage, the cost of installation of the sensor nodes (SNs) and fuzzy-based lifetime in the 3D environment is considered. Sensor nodes $\mathbf{X} = \{x_1, x_2, \ldots, x_n\}$ show all the possible positions for deployment in the storage areas, and each SN has an initial battery level b_i^o and p+1 sensing range options $\mathbf{R} = \{r_{i0}, r_{i1}, \ldots, r_{ip}\}$. The corresponding energy consumption $\mathbf{E} = \{e_{i0}, e_{i1}, \ldots, e_{ip}\}$ depends on the Euclidean distance between the SNs and relay nodes (RNs). Referring to Equation 3.1, the energy consumption of SNs is suggested to be a quadratic form, and the total consumed energy c for an activation time interval a_j can be evaluated (Wu et al., 2018).

$$\mathrm{c} = e_{ij} \cdot a_j \text{ ,where } e_{ij} = \mathrm{e}_{ip}(\frac{r_{ij}}{r_{ip}})^2 \tag{3.1}$$

Differing to the traditional approach on evaluating system lifetime, the proposed system lifetime factor considers the effect of operating temperature which influences the battery capacity in the ESN. Thus, a fuzzy temperature window is adopted to adjust the ESN battery level so as to enhance the system lifetime estimation. The initial battery level b_i^o of SN$_i$ is thus multiplied by the fuzzy membership function $\delta_\mathrm{i}(\mathrm{temp}_i): \mathbb{R} \to [0,1]$, where $[b_i^s,\ b_i^e]$ and $[l_i, u_i]$ represent the best and acceptable operating temperature for SNs, respectively, as in Equation 3.2. Overall, the expected activation time interval can be modelled, as in Equation 3.3, for the connection between a sensor node SN_i and the closest RN_j.

$$\delta_i(\mathrm{temp}_i) = \begin{cases} 0, & \text{if } \mathrm{temp}_i < l_i \\ \dfrac{\mathrm{temp}_i - l_i}{b_i^s - l_i}, & \text{if } l_i \leq \mathrm{temp}_i < b_i^s \\ 1, & \text{if } b_i^s \leq \mathrm{temp}_i \leq b_i^e \\ \dfrac{\mathrm{temp}_i - u_i}{b_i^e - u_i}, & \text{if } b_i^e < \mathrm{temp}_i \leq u_i \\ 0, & \text{if } \mathrm{temp}_i > u_i \end{cases} \tag{3.2}$$

$$a_i = \frac{b_i^o \cdot \delta_i(\mathrm{temp}_i)}{\mathrm{e}_{ip}[\frac{\min(r_{ij})}{r_{ip}}]^2} = \frac{b_i^o \cdot \delta_i(\mathrm{temp}_i) \cdot \mathrm{e}_{ip} \cdot {r_{ip}}^2}{\min(r_{ij})^2} \tag{3.3}$$

On the other hand, the cost objective for SNs can be established by considering the subtraction of the ratio of deployed SNs and the total number of possible positions for SNs from unity. The objective functions for maximization in the first deployment stage is summarized as in Equation 3.4.

$$\mathrm{f}_1^{\mathrm{SN}} = \left[1 - \frac{1}{n}\sum_{i=1}^{n} x_i\right] \text{ and } \mathrm{f}_2^{\mathrm{SN}} = \left[\frac{\sum_{i=1}^{n} a_i x_i}{a_{\max}\sum_{i=1}^{n} x_i}\right] \tag{3.4}$$

3.3.3.2 *Stage 2: Relay Node Deployment*

The second stage considers the cost of installing RNs and the connectivity for formulating the corresponding objective function for relay node deployment. Similar to the SN deployment, the cost of RNs is measured by subtracting the ratio of deployed RNs and the total number of possible positions for RNs, i.e. $\mathbf{Y} = \{y_1, y_2, \dots, y_m\}$, from unity. Thus, the ratio of not deploying RNs can be measured, which should be maximized for minimizing the cost. For measuring the connectivity of each RN, a matrix $R_{ij} = (r_{ij}) \in \mathbb{R}^{nxm}$ is established to determine the distance r_{ij} between SN_i and RN_j. Subsequently, SN_i is assigned to the closest RN_j in terms of Euclidean distance, and is then normalized to the Boolean output, which implies that the connection between SN_i and RN_j is built. The connectivity factor ρ for each RN_j can be modelled through summing all the normalized outputs as in Equation 3.5. The objective functions of RN deployment can then be established taking cost and connectivity into consideration, as shown in Equation 3.6.

$$\rho_q = \sum_{i=1}^{n} \frac{\min\,(r_{i1}, \dots, r_{im})}{|\min\,(r_{i1}, \dots, r_{im})|}, \exists q \in [1, m] \tag{3.5}$$

$$\mathrm{f}_1^{\mathrm{RN}} = \left[1 - \frac{1}{m}\sum_{j=1}^{m} y_j\right] \text{ and } \mathrm{f}_2^{\mathrm{RN}} = [\frac{\sum_{j=1}^{m} \rho_j\, y_j}{\sum_{j=1}^{m} y_j}] \tag{3.6}$$

3.3.3.3 *Stage 3: IoT Technology Deployment*

Regarding the IoT technology deployment, the SNs are deployed for collecting ambient temperature (K) and relative humidity (%) in the physical layer, while RNs are used to transmit the collected data to the IoT development platforms. The collected data by using IoT technologies are formulated for the real-time monitoring and environmental mapping in the indoor areas. To study the heating, ventilation, and air conditioning (HVAC) airflow in the environmental mapping analysis, variations of temperature and relative humidity in the storage areas are evaluated. However, it is expensive to deploy the large number of SNs and RNs according to the WHO method (WHO TRS 961). Therefore, the aim is to minimize the number of SNs and RNs used in the ESN, while maintaining the airflow performance. To achieve this objective, the maximum number of SNs should be deployed first, and the global mean temperature and global relative humidity are then measured. The airflow problems are modelled to maximize the deviations to the global mean temperature and humidity from the set of deployed SNs in the baseline method. The concept of the coefficient of variation is then applied to evaluate the ratio of the standard deviation of the set of deployed SNs and the global mean value, and to formulate the objective functions as in Equations 3.7 and 3.8. Therefore, the maximized deviations from the specific set of deployed SNs and RNs to the global mean values (with regards to temperature and relative humidity) can be obtained.

$$\mathrm{f}_1^{\mathrm{ES}} = \frac{1}{\mu_{\mathrm{global}}^{\mathrm{temp}}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(\mu_i^{\mathrm{temp}} - \mu_{\mathrm{global}}^{\mathrm{temp}})^2 \cdot x_i}{\sum_{i=1}^{n} x_i}} \tag{3.7}$$

$$\mathrm{f}_2^{\mathrm{ES}} = \frac{1}{\mu_{\mathrm{global}}^{\mathrm{humi}}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(\mu_i^{\mathrm{humi}} - \mu_{\mathrm{global}}^{\mathrm{humi}})^2 \cdot x_i}{\sum_{i=1}^{n} x_i}} \tag{3.8}$$

The above six objective functions can be combined to form the maximization problem, and are subjected to the following constraints: (i) β-degree fault tolerance of SN-RN pairs determined by at most β_i possible RN connections for the deployed SN$_i$, i.e. $\sum_{i=1}^{n} \beta_i x_i / \sum_{i=1}^{n} x_i \geq \beta_0$, (ii) maximum connectivity (C_{RN}) of RNs, i.e. $\rho_j \leq C_{RN}$, and (iii) coverage of deployed SNs (C_{SN}) considering the union of the covered area of SN$_i$ and number of covered grid points, i.e. $\bigcup_{i=1}^{n} \mathrm{g}(x_i) \geq C_{SN}$. The function g($x_i$) is formed to measure the number of grid points covered by the deployed SNs. The binary integrality is stated as $x_i, y_j \in [0, 1]$.

3.3.3.4 Multi-objective Optimization for the Deployment Problem

To solve the above maximization problem, one of the common multi-objective optimization techniques, i.e. NSGA-II, is considered (Deb et al., 2002). The genetic operations of NSGA-II consist of tournament selection, two-point crossover, and mutation (Wang et al., 2017). To enhance its computational efficiency further, and validate its optimality, multi-response Taguchi-guided k-means clustering (MTK) is proposed. This is achieved by integrating the multi-response Taguchi method and k-means clustering into the GA, with the aim of minimizing the computational time and optimizing the fitness functions. Therefore, the MTK-embedded GA (MTKGA) is developed to solve the aforementioned optimization problem in ESN deployment for environmental mapping. The core concept is to apply k-means clustering to create an initial population with better fitness values, instead of initializing the chromosomes randomly, as shown in Figure 3.6. In addition, four parameters are optimized by the multi-response Taguchi method to search for the best parameter setting in view of computational time and search performance. These four parameters are as follows: (i) crossover rate, (ii) mutation rate, (iii) population size, and (iv) number of clusters in k-means clustering.

At the beginning of the MTKGA, the aforementioned parameters are initialized with four corresponding levels, namely crossover rate: 0.2/0.4/0.6/0.8, mutation rate: 0.005/0.01/0.05/0.1, population size: 50/100/200/400, and cluster number: 2/3/4/5. According to the above parameter information, the orthogonal array L_{16} (4^4) is established for conducting the minimal number of experiments $\boldsymbol{T} = \{c_l, m_l, p_l, k_l\}$. The minimal number of experiments to be conducted, i.e. N_{min}, is obtained by considering the number of levels L_i for parameter I, as in Equation 3.9.

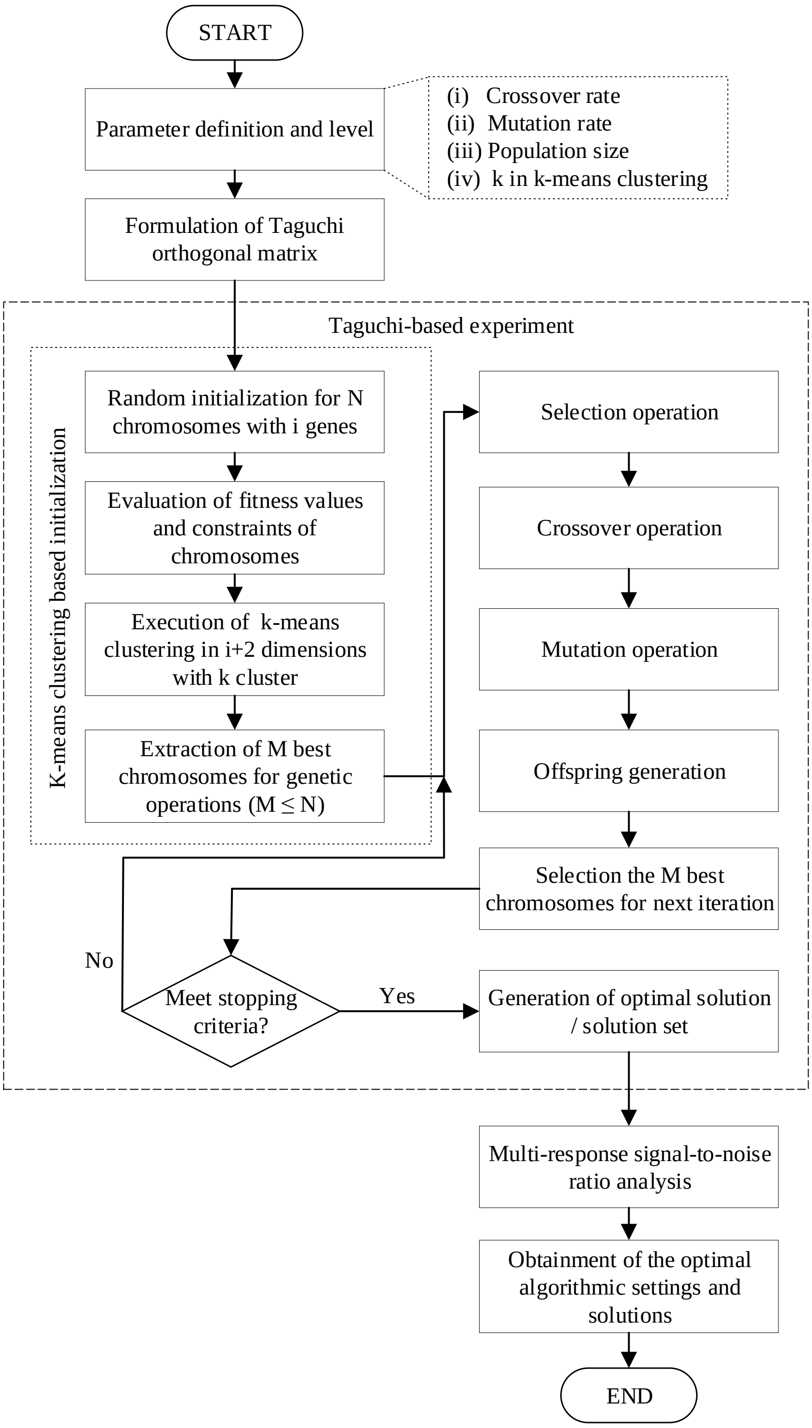


Figure 3.6 Process flow of the proposed MTKGA

After the system initialization, genetic operations are then commenced in accordance with the parameter settings given by the Taguchi method. First of all, an initial population is formulated by using k-means clustering to produce the chromosomes with better fitness values. A population set is generated randomly, and the fitness values and constraint satisfaction are then evaluated. Based on the cluster number k_l, the random k_l centroid coordinates are formulated, and the Euclidean distance d between the chromosomes and centroid coordinate are thus measured. To stop the initialization, two criteria should be met, namely (i) no change observed in the centroid coordinates, and (ii) a sufficient population size is obtained. Genetic operations are then conducted to search for the pareto optimal solutions, including the steps of tournament selection, two-point crossover and mutation, which are the standard process in NSGA-II. Overall, the termination criteria of the proposed MTKGA are (i) to reach the maximum defined number of iterations, and (ii) to obtain the improvement of the spread of the solution set $\leq 10^4$. Subsequently, the signal-to-noise ratio (φ) of response in fitness values f_{ij} and computational time t_i are then evaluated, as in Equation 3.10. To obtain the results from the multiple responses in the Taguchi method, the signal-to-noise ratios are normalized and averaged to locate the optimal settings in the problem. The responses $\varphi = \{\varphi_1, \varphi_2, \ldots, \varphi_u\}$ for all experimental settings u can be measured, and thus the average signal-to-noise ratio $\overline{\varphi_{ijr}}$, for parameter i, its level j and response k, can be computed. The normalization of the ratios is derived from Equation 3.10 to obtain the normalized weight ω_{ijk}, and the response

R_k of the execution time t and crowding distance d_c, as in Equation 3.11. Therefore, the normalized weights can be averaged to obtain the best parameter settings by integrating the multi-response Taguchi method.

$$N_{min} = L_1 + \sum_{i=2}^{r} (L_i - 1) \tag{3.9}$$

$$\varphi_u = \begin{cases} -10 \cdot \log\left(\frac{1}{n}\sum_{e=1}^{\mathrm{N_{min}}} t_e^2\right), \text{where } k = t \\ -10 \cdot \log\left(\frac{1}{n}\sum_{e=1}^{\mathrm{N_{min}}} \frac{1}{f_{ej}}\right), \text{where } k = f \end{cases} \tag{3.10}$$

$$\omega_{ijk} = \begin{cases} \frac{\max_r\left(\overline{\varphi_{ijr}}\right)}{\overline{\varphi_{ijr}}}, \text{for STB}, \overline{\varphi_{ijr}} < 0 \text{ and } r \in R_k \\ \frac{\overline{\varphi_{ijr}}}{\max_r\left(\overline{\varphi_{ijr}}\right)}, \text{for STB}, \overline{\varphi_{ijr}} \geq 0 \text{ and } r \in R_k \end{cases} \tag{3.11}$$

By using MTKGA, a pareto solution set and pareto frontier can be formulated, and the spread of solutions and convergence of solutions can be improved. According to the requirements of environmental monitoring and mapping, the deployment scheme of ESN can be established to install the critical SNs and RNs to balance the effectiveness and cost for the implementation. Further, an individual in the ESN deployment is represented as [**X**, **Y**], incorporating the number of possible SNs and RNs in a 3D environment, as shown in Figure 3.7.

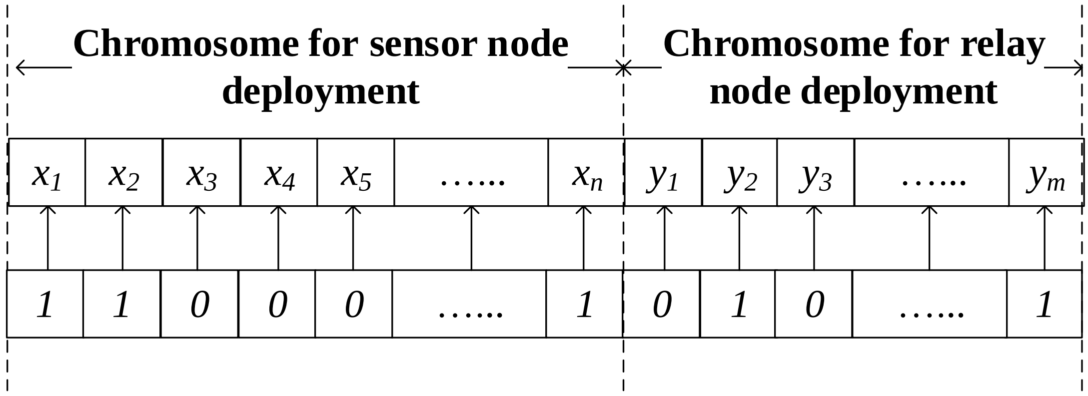


Figure 3.7 Individual representation of the ESN deployment problem

3.4 Blockchain-enabled Data Management Module (BDMM)

To share the collected data in the supply chain network, blockchain technology is deemed to be promising by integrating the IoT for achieving reliable data management and real-time data collection. Subsequently, the food traceability can be built and facilitated in the PFEC environment. According to the development of blockchain technology, the advantages of high security, decentralized control, distributed information, decentralized consensus, data transparency and auditability can be gained in the distributed supply chain network. However, the direct deployment of existing blockchain mechanisms may lead to several negative effects in the areas of food traceability and shipment activity tracking. Firstly, the existing consensus algorithms may not be applicable to drive the process of block validation and forging in the blockchain, as mutual consensus cannot be reached in the peer-to-peer supply chain network. Secondly, when considering the use of blockchain-IoT technologies, it is ineffective to store all the real-time data from the PFEC in the blockchain, which may cause the inefficiency in blockchain creation and validation. The RIM, mentioned in Section 2.4.4 should be considered to design feasible and effective blockchain-IoT solutions for the food traceability and shipment activity tracking. Thirdly, storing unlimited data in the blockchain regarding supply chain information may also cause inefficiency in the blockchain-IoT applications as high levels of system memories and capabilities are required. Therefore, the definitive end of the blockchain should be considered for such an industrial application such that the useless section of blockchain can be vaporized to the cloud database for better data management. Thus, a hybrid approach of blockchain-IoT technologies for light-weight and vaporized characteristics is proposed (Tsang et al., 2019b).

3.4.1 Blockchain Security and Structure

Regarding the deployment of blockchain for data management and IoT data acquisition, the blockchain structure and security mechanism have two core and fundamental components. The structure of the blocks in the blockchain consists of six elements, namely index, timestamp, data, self-hash value, previous hash value and random number (i.e. nonce). The index shows the sequence order of the blockchain and indicates the position of the particular blocks. Timestamp and data represent the time of data creation and the data to be stored in the blockchain, such as transaction activities, respectively. The self-hash value is the encryption result of the blocks by using a secure hash algorithm (SHA), such as SHA-256. The hash algorithm is a one-way function to convert the data and message to a 256-bit (32-byte) string, which is infeasible to be reverted to obtain the input by considering output, and therefore brute force attack is the only way to decrypt the hash values in output. For instance, SHA-256, which is under the family of SHA-2, generates a hash value with the length of 256 bits by inputting the specific messages and data. The previous hash is referred as the hash value in the previous block, i.e. the block n-1. Also, the nonce is a random or pseudo-random value to modify the block messages so as to fulfil the particular target difficulty in block validation.

To create the blockchain, the first block at the beginning of the whole blockchain is called the genesis block, which has “0” values in the index and previous hash values. To create the data block in the blockchain, asymmetric cryptography is applied to secure the block creation process to protect the user configuration and credential information. Asymmetric cryptography is the improved version from the symmetric cryptography, where the keypairs become the private key and public key, instead of using a shared key. The private key has a role like a password of a node and an account with the identification information, but it is not publicly available and the owners should not share it with others. The functions of the private key are to access, authorize and control the accounts for the activities in the network. On the other hand, the role of the public key is like a username, which can be shared with anyone. There is an association between the public key and private key, but it is not feasible to derive the private key from the public key. For example, in sending confidential data from the sender to the receiver, the data can be encrypted by the receiver's public key, and the receiver can decrypt by using a private key. Subsequently, digital signatures are proposed by using the asymmetric cryptography in the blockchain as a promising tool for sending messages and data between various parties. For instance, if user A would like to distribute a particular message in the distributed network, the message can be encrypted by using A's private key and other users can decrypt it by using A's public key. Thus, the message is digitally signed by user A. Also, if user A would like to send another message to user B privately, the message should be encrypted by using A's private key and B's public key accordingly. The message can only be opened by using A's public key and B's private key so that the message can only be received by user B. Particular to the applications of cryptocurrency, the cryptocurrency address is used to represent the public key, and is derived from the public key by means of one-way hash algorithms.

In addition, when there are more than one messages and data to be encrypted, the Merkle tree is applied to formulate the Merkle tree root in the block. The Merkle tree is the binary tree to manage multiple hash values from the transactions, data and messages. Figure 3.8 shows an example of creating a Merkle tree by six corresponding data hashes, i.e. A, B, C, D, E, and F. By adopting the hash function, the data can be converted to the corresponding hash values, and the hash values are then combined two by two, for example HA + HB = HAB. Eventually, the entire Merkle tree can be established to manage multiple data in the blockchain effectively, and the top of the Merkle tree is called the Merkle tree root.

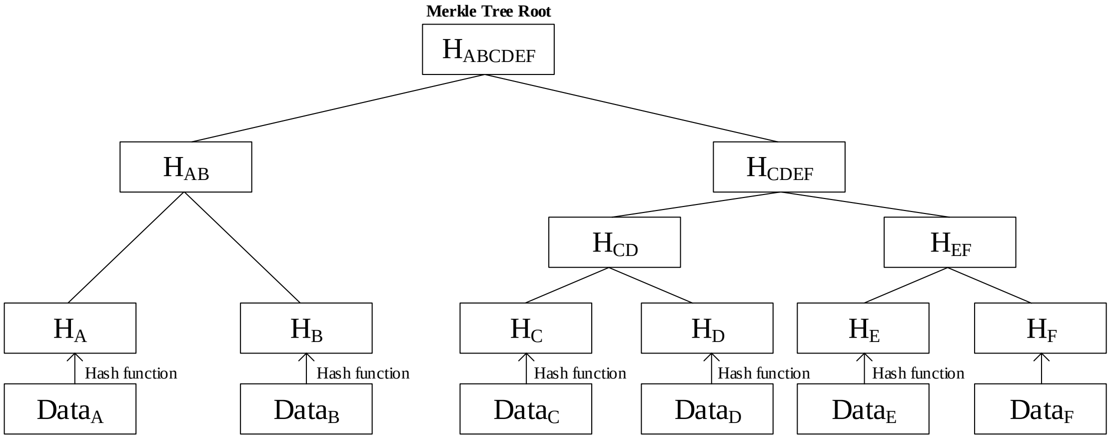


Figure 3.8 Graphical illustration of Merkle tree structure in blockchain

Overall, the nodes can effectively create messages, data and transaction activities in the distributed network. In view of the target difficulty in block validation, it is referred to the restrictions of the specific beginning values in the output bytes, and thus the nonce is used to adjust the output hash values for meeting the requirements. Tables 3.1 and 3.2 show the notation and pseudo code of block forging process to demonstrate the target difficulty, respectively. The function of uint32( ) is used to formulate a nonce value, and thus it is inputted in the function of ft.Blockchain.calculate_hash( ) for generating the desired format of output hash values. The difficulty in the block forging process is used to control the update frequency of the entire blockchain, and to ensure complete synchronization in the distributed network. A shorter time used for block forging process is preferred because the control of update frequency by adjusting the target difficulty in the blockchain can be more precise.

Table 3.1 Notation of the block forging process

Notation	**Definition**
data	Data string to be stored in blockchain
hash	Current hash value for the block generated by SHA256
i	Number of iterations for block forging process
idx	A numerical value in the type of double
index	Index of the block sequence
nonce	A numerical value in the type of uint32
N_{zero}	Target difficulty and restriction for hash value formulation in the block forging process
p_hash	A hash value in the previous block
t	Time in second used for block forging process
t_{delay}	A buffer and delay time for the block forging process
timestamp	Timestamp data to be recorded in the blocks
uint8_sha256	Output hash string from the function of ft.Blockchain.calculate.hash()

Table 3.2 Pseudo-code of block forging process

Function 1: Block forging with designated target difficulty

```
function [$i$ , $t$] = forge(index, p_hash, timestamp, data)
Set value of difficulty $N_{zero}$; Set process delay time $t_{delay}$; Set number of iterations
$i \leftarrow 1$;
Start of the stopwatch timer, tic;
for (idx from 0 to $2^{32}$) do
    nonce = uint32(idx);
    [hash, uint8_sha256] = ft.Blockchain.calculate_hash(index, p_hash, timestamp, nonce, data);
    if first $N_{zero}$ bits of hash string, uint8_sha256, are equal to 0 then
        break;
    end if
    Pause the process with $t_{delay}$;
    $i \leftarrow i+1$;
end for
$t \leftarrow$ end of the stopwatch timer, toc;
end function
```

3.4.2 Integrated Consensus Mechanism

After the block creation in the blockchain, the block validation is also the essence for creating the trust and consensus regarding the shared data in the distributed network. To achieve mutual trust and consensus, the formulation of an appropriate consensus mechanism is needed. PoW is a well-developed consensus mechanism for mining blocks for the cryptocurrency applications, but huge energy consumption and computational resources to complete with other miners are required. In order to improve the effectiveness of the consensus establishment, PoS was thus proposed to forge and mint blocks, where the mining process in PoW was modified to the validation process by a group of validators in the distributed network. Through integrating the essence of the existing consensus mechanisms, proof of supply chain share (PoSCS) is proposed, in which the supply chain stakeholders act in the role of validators who are responsible for forging and minting blocks so as to facilitate the operations of blockchain applications. The responsibility and share of the supply chain parties is aggregated into a normalised supply chain share (S_i) to decide the validator of the block, as in Equation 3.12, where i represents a designated supply chain party with total number of parties **N**. Assuming that the whole journey of food supply chain can be divided into m sections in total cycle time T, each section is performed by a designated party. Thus, the time used in PFSC for each party is considered in S_i, where x_j denotes a binary variable representing j supply chain activities, and its corresponding required time is t_j. Also, the integrality of S_i is expressed as $\sum_{i=1}^{n} S_i = 1$. Only considering the transit time is insufficient as some parties may hold the goods for a long period of time without the extensive values contributing to the traceability process. Therefore, the perceived values from the traceability system for supply chain stakeholders are considered, and they are analysed by four factors, namely the influence factor *INF*, interest factor *INT*, devotion factor *DEV*, and satisfaction factor *SAT* (Pang et al., 2015). *INF* indicates the ability of promoting the traceability systems to other stakeholders; *INT* is the willingness of the stakeholder to achieve benefits from traceability systems; *DEV* shows the extent of devoting their resources to formulate traceability systems; *SAT* is the level of satisfaction after formulating the traceability systems. The weighting α between *INT* and *DEV* is adjusted to determine the appropriate assessment strategy, and the score *R* of *INF*, *INT*, *DEV* and *SAT* is defined as $[R_l, R_u]$. To aggregate the average transit time and added value in PFSC, a weighting β is considered to combine the above two components such that S_i is normalised to a range of (0,1]. Therefore, the PoSCS can play the role of PoS in cryptocurrency to assign the validator to forge the new block in the blockchain objectively.

$$S_i = \frac{1}{|T|}\sum_{j=1}^{m} x_{ij}t_j \cdot \frac{\{INF_i \cdot SAT_i \cdot [\alpha INT_i + (1-\alpha)DEV_i]\}}{|\Delta R^3|}, \forall i \in N \qquad (3.12)$$

However, the above normalized supply chain share cannot reflect the level of active participation of the stakeholders, and thus their shipment volume V(*t*), which is updated in a specific time interval *t*, in the complex supply chain network is considered to formulate a dynamic state in the supply chain share as in Equation 3.13. The shipment volume refers to all inbound and outbound shipments regarding upward and downward supply chain activities for a specific supply chain stakeholder, as shown in

Fig. 3.9. Consequently, the dynamic supply chain share $\widehat{S_\iota(t)}$ can be established to reflect the stakeholders' level of active participation in supply chain activities.

$$\widehat{S_\iota(t)} = \frac{V(t)}{V(t-1)} \cdot S_\iota\widehat{(t-1)} \tag{3.13}$$

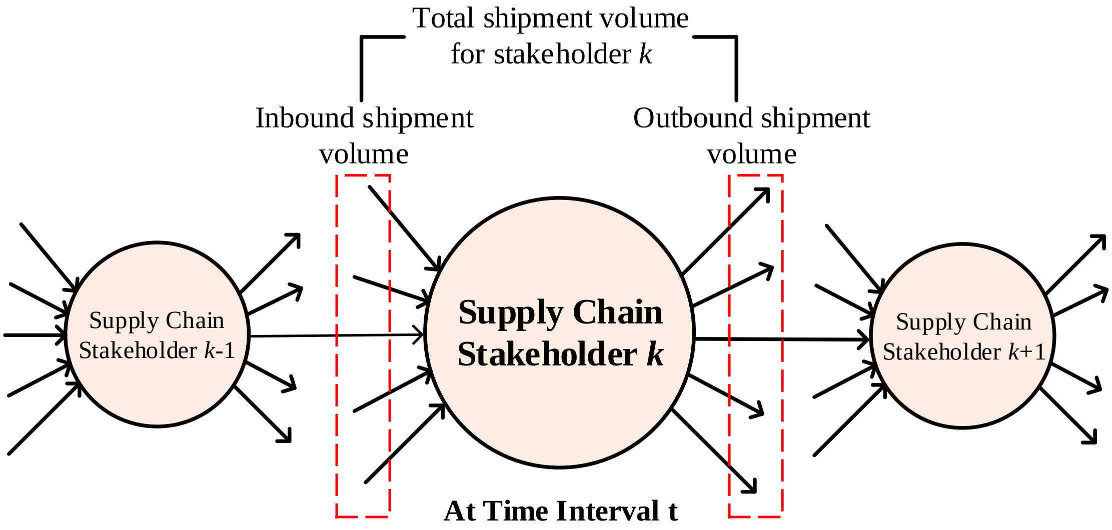


Figure 3.9 Graphical illustration on the dynamic update of PoSCS

3.4.3 Hybrid Data Flow with Cloud

The entire blockchain is the series of blocks created and validated in the distributed P2P network, as shown in Figure 3.10. Strictly speaking, each block can be defined to have (i) a block header and (ii) a block body. The block header contains information about the block itself, including the index (data type: int), previous hash value (data type: varchar), timestamp (data type: varchar), difficulty target (data type: int) and nonce (data type: int). The block size covering both the block header and body is usually less than 1 MB. The difficulty target refers to the restriction on the results of hash value by entering the messages and data through the adjustments of nonce. It is used to control the synchronization time and interval of the entire blockchain application. In the block body, it is mainly for the messages and data to be stored.

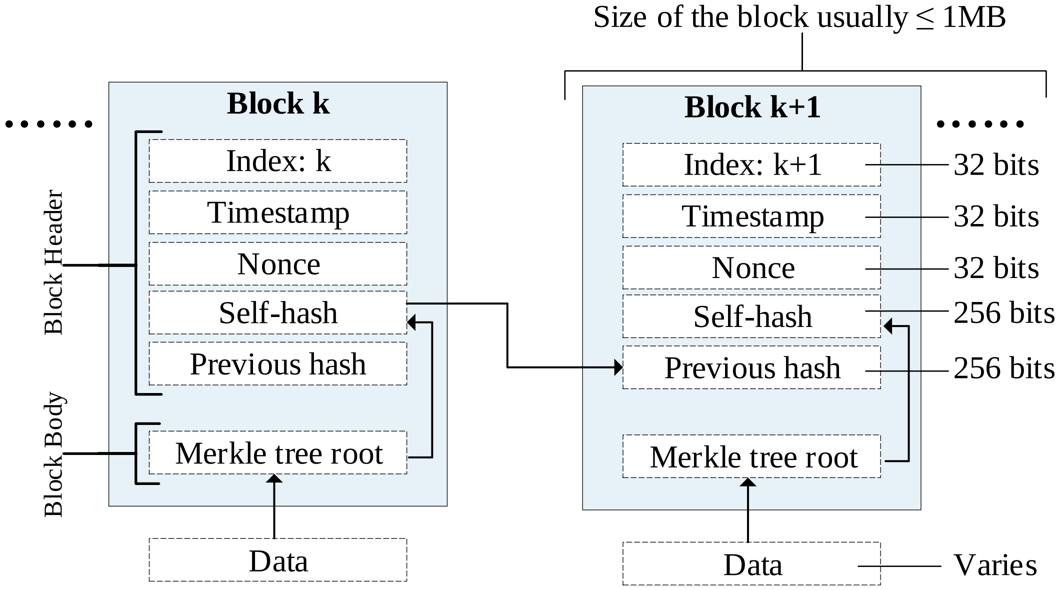


Figure 3.10 Sequence of created and validated blockchain

Regarding the integration between the blockchain, IoT and cloud technologies, a hybrid approach is considered so that the feasibility and scalability of the blockchain-enabled IoT system for food traceability can be maintained. The balance between real-time data acquisition, data storage and data sharing can be effectively struck. Although the data stored in the blockchain are secure and reliable for sharing and synchronizing the users in the distributed network, the design of the blockchain is not for storing the tremendous operational and real-time data. Therefore, the concept of RIM, mentioned in Section 2.5.4, is integrated in the above hybrid approach. The events or data payload IDs generated from IoT interactions are stored in blockchain for products to associate with real-time data in the cloud database. Therefore, the light-weight data blocks and efficient blockchain applications can be formulated, as shown in Fig. 3.11, such that minimal data are operated in blockchain to improve system adaptability and flexibility. When customers purchase perishable food in the e-commerce platforms, smart contracts are formulated to acknowledge the purchases and entitlement to access food traceability records. In view of the food life cycle in the supply chain, definite start and end nodes are required to specify the length and duration of the blockchain. Differing to blockchain applications in cryptocurrency, it is unnecessary to carry all relevant data in the applications for food traceability, which may have a negative impact on computational efficiency. Hence, the mechanism of blockchain vaporization is developed for achieving reliable food traceability effectively. A batch of food is supplied from farmers and processed by food processors, and thus the batch ID (farm) can be assigned to the food for creating the genesis block. Along the supply chain journey, the fluctuation of environmental conditions and activity tracking can be monitored and recorded in the Cloud database and blockchain. Along the supply chain, the container ID, batch ID (finished goods) and lot ID are recorded to identify and trace the food items. The blockchain for the food traceability is then vaporized after completion of either the point of sales or proof of delivery activities. The vaporized blockchains are then stored in the cloud database for releasing storage space and system memory.

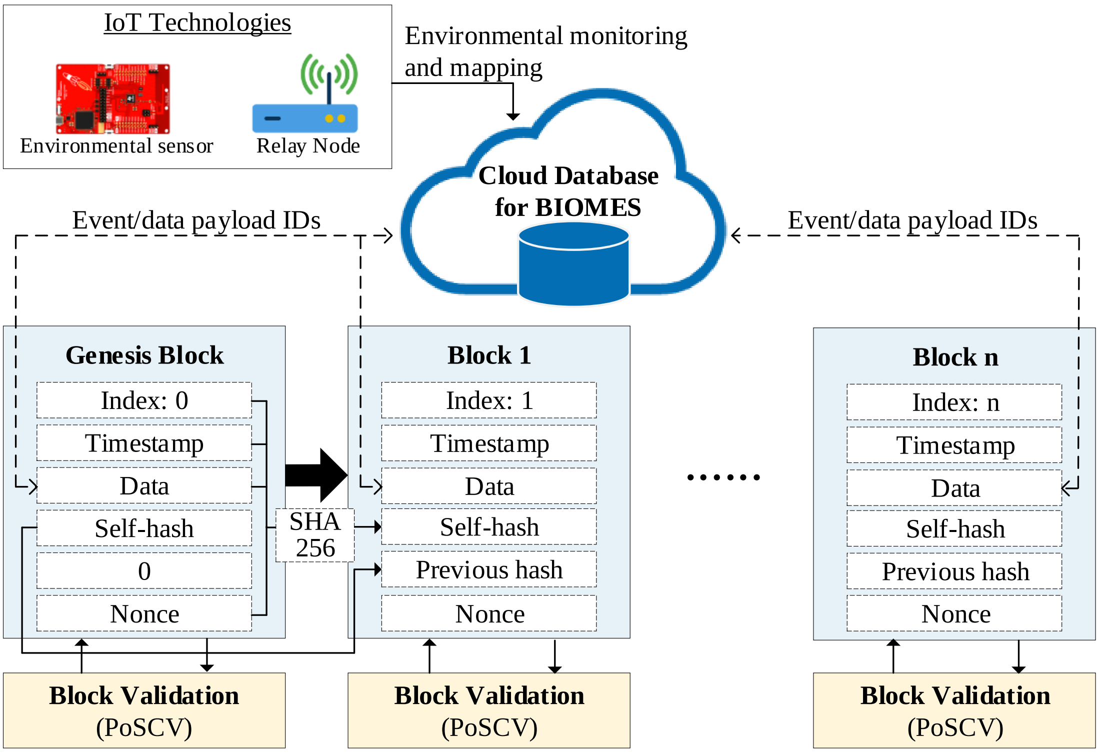


Figure 3.11 Hybrid formulation between blockchain, IoT and cloud computing

3.5 Food Quality Management Module (FQMM)

The aforementioned sections present an integrated blockchain-IoT approach for data collection and management, which is one of the enhancements in PFEC in the area of food monitoring and traceability. To further improve the MTEF process, the functionalities of food quality management should be improved by means of cold chain passive packaging, multi-temperature delivery route planning and fuzzy food quality assessment. Thus, the food quality in the PFEC businesses can be effectively guaranteed and customized, starting from the e-fulfilment center to the receipt by end customers.

3.5.1 Fuzzy Food Quality Assessment

After data acquisition from IoTDM and BDMM, information of the shipment journey, activity milestones and environmental conditions can be used to establish a dynamic food quality evaluation in PFSC. To effectively evaluate the food quality, sensor data collected and managed by blockchain IoT technologies need to be pre-processed and structured. The measurements of mean kinetic temperature (MKT) and mean kinetic relative humidity (MKRH) are applied to obtain the corresponding values to represent the effects of variations of temperature and relative humidity over a period of time (Peters et al., 2012). It is misleading to use arithmetic mean of temperature and relative humidity to represent the fluctuation of environmental conditions in supply chain process. Also, the isolated evaluations of MKT and MKRH lack the consideration in the variability of temperature and relative humidity. Consequently, MKT and MKRH for temperature and relative-humidity variability should be applied to evaluate the actual situations faced by the perishable food. For measuring the MKT, the fluctuations of temperature **T** = $\{T_1, T_2, \ldots, T_o\}$ and relative humidity **RH** = $\{RH_1, RH_2, \ldots, RH_o\}$ over transit time intervals t = $\{t_1, t_2, \ldots, t_o\}$ are considered, as in Equation 3.14, where E_a is activation energy, R is the gas constant, B is the moisture-sensitivity and RH_c is the constant within the range of variable relative humidity. Similarly, MKRH is evaluated over certain period of transit time as in Equation 3.15, where T_c is the constant value within the range of variable temperature. Subsequently, MKT and MKRH can be obtained for effectively measuring the aggregated temperature and relative humidity which simulate the effects of variable handling temperature and relative humidity.

$$\text{MKT} = \frac{E_a}{R[B(RH_c) - \varphi]}, \text{where } \varphi = \ln\left(\frac{\sum_{i=1}^{o} t_i e^{[B(RH_i) - \frac{E_a}{R \cdot T_i}]}}{\sum_{i=1}^{o} t_i}\right) \tag{3.14}$$

$$\text{MKRH} = \frac{E_a}{B \cdot R \cdot T_c} + \frac{\varphi}{B}, \text{where } \varphi = \ln\left(\frac{\sum_{i=1}^{o} t_i e^{[B(RH_i) - \frac{E_a}{R \cdot T_i}]}}{\sum_{i=1}^{o} t_i}\right) \tag{3.15}$$

To achieve dynamic food quality evaluation, MKT, MKRH, sensory score and variation of total transit time are taken into consideration to formulate three outputs, namely shelf life adjustment, quality decay rate, and order of quality decay. The quality decay evaluation is then established according to the Arrhenius's equation. To adopt fuzzy logic for dealing with the above considerations, membership functions of input and output parameters and fuzzy rules in the form of IF-THEN rules are needed. Parameters are required to be fuzzified from crisp values to fuzzy sets in the fuzzy logic, such as "low", "medium" and "high", so as to express linguistic terms by membership functions. Equation 3.16 shows the fuzzy set $\tilde{F}$ for parameter $Z = \{z_1, z_2, \ldots, z_p\}$ with the corresponding belongingness $\mu_{\tilde{F}}$. Membership functions are then formulated by combining various fuzzy sets. On the other hand, the fuzzy rules, which show the antecedent and consequent relationship between input and output parameters, are stored in the knowledge repository for the use of inference engine.

$$\tilde{F} = \sum_{k} \frac{\mu_{\tilde{F}}(z_k)}{z_k} \tag{3.16}$$

The entire fuzzy logic approach has three major components, namely fuzzification, inference engine and de-fuzzification. In fuzzification, the input parameters are fuzzified by their pre-defined membership functions, where crisp values are converted into fuzzy sets with specific membership values. After this, the membership values are aggregated by using Mamdani-type fuzzy inference and fuzzy

IF-THEN rules. The inference process is expressed as in Equation 3.17, where the OR operator is applied to establish a bounded area in the output membership functions. By considering rule *r*, the input parameters *X* is converted to corresponding membership values, and the composition of input fuzzy sets can be obtained. Thus, the output fuzzy sets *Y* are formulated and defined in output membership functions. In the de-fuzzification, fuzzy sets are converted into output crisp values *Y'* by using the centroid method with weighting *ω*, which evaluates the centre of gravity in the output bounded areas as in Equation 3.18.

$$\mu_{F_i}(Y_i) = \max\left\{\min_j \left[\mu_{F_{1r}}(X_1), \mu_{F_{2r}}(X_2), \ldots, \mu_{F_{qr}}(X_q)\right]\right\} \tag{3.17}$$

$$\mathrm{Y}_i' = \frac{\int \omega_i \cdot Y_i \cdot \mu_{F_i}(Y_i)\, dY}{\int \omega_i \cdot \mu_{F_i}(Y_i)\, dY} \tag{3.18}$$

Subsequently, the shelf life adjustment can be obtained to modify the pre-determined food shelf life based on the situation in the shipment journeys. Also, the quality decay can be formulated by using the Arrhenius equation as in Equation 3.19, where a relationship is built between food quality *q* and transit time *t* at the specific temperature, with a certain rate of quality decay *k* and order of quality decay *n* (Ling et al., 2015). Combining the above information, the food traceability not only provides shipment and product information to the stakeholders, but also includes the temperature excursion management and shelf life monitoring.

$$\frac{\Delta q}{\Delta t} = \pm k q^{n} \tag{3.19}$$

3.5.2 Cold Chain Passive Packaging

In this section, the design and development of cold chain passive packaging for assisting the MTEF process in PFEC businesses is presented. To evaluate the best packaging options and determine the maximum time allowed for transportation, a set of experiments can be conducted by using the Taguchi method with the establishment of an L_9 (3 × 3 × 3) orthogonal array. Table 3.2 shows the corresponding packaging materials, including (i) three different sizes of polyfoam boxes, (ii) three different volumes of eutectic plates, and (iii) three different numbers of eutectic plates used. To maintain the data accuracy and reduce the variation, three sets of the experiments were conducted to measure the optimal packaging setting for specific perishable food. Figure 3.12 shows the set-up for the experiments for recording the change of temperature and relative humidity over time in the passive packaging setting, where the data logger, namely Elitech RC-4HC, is adopted for data collection for all the experiments. Subsequently, the recorded data can be visualized to investigate the rate of change of temperature and relative humidity over time. Concerning the Taguchi method, there are six major stages to measure the optimal settings and dominant factors, including objective formulation, factor identification, design of experiment, conducting experiment, data analysis, and validation. Perishable food has its own recommended handling conditions in the range of upper and lower specifications of temperature and relative humidity, i.e. $[Temp_{lower}, Temp_{upper}]$ and $[Humi_{lower}, Humi_{upper}]$. By making use of the graph obtained from the data recording in different packaging settings, T(x) and H(x), which are two functions for expressing rate of change of temperature and relative humidity over time, can be determined, with $T^{-1}(x)$ and $H^{-1}(x)$ as their inverse functions. Combining the recommended handling conditions, the maximum time for satisfying the conditions, in the overlapping range (φ_i) between $[T^{-1}(Temp_{lower}), T^{-1}(Temp_{upper})]$ and $[H^{-1}(Humi_{lower}), H^{-1}(Humi_{upper})]$ can be obtained, as shown in Figure 3.13. In other words, it shows the maximum time to handle the specific perishable food in the defined packaging settings. Moreover, preparation time for formulating the packaging settings is needed to define the time from the starting point to reach the minimum point in the overlapping range, i.e. $\min\{\varphi_i\}$. When considering multiple overlapping data ranges simultaneously, the maximum value among all data values in different testing packaging settings is selected as the maximum time allowed for transportation in specific packaging settings, i.e. max $\{\varphi_i : i \in \mathbb{N}\}$. Table 3.3 shows the identified factors in the experimental studies, in which the three investigated factors have their own three corresponding levels. Also, for the design of experiments, the full factorial design with the orthogonal array of the Taguchi method L_9 (3 × 3 × 3) is formulated, as shown in Table 3.4.

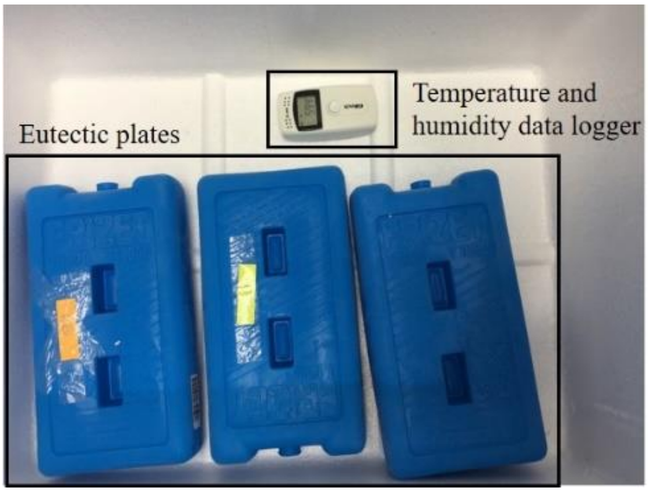


Figure 3.12 Example of experiments for passive packaging

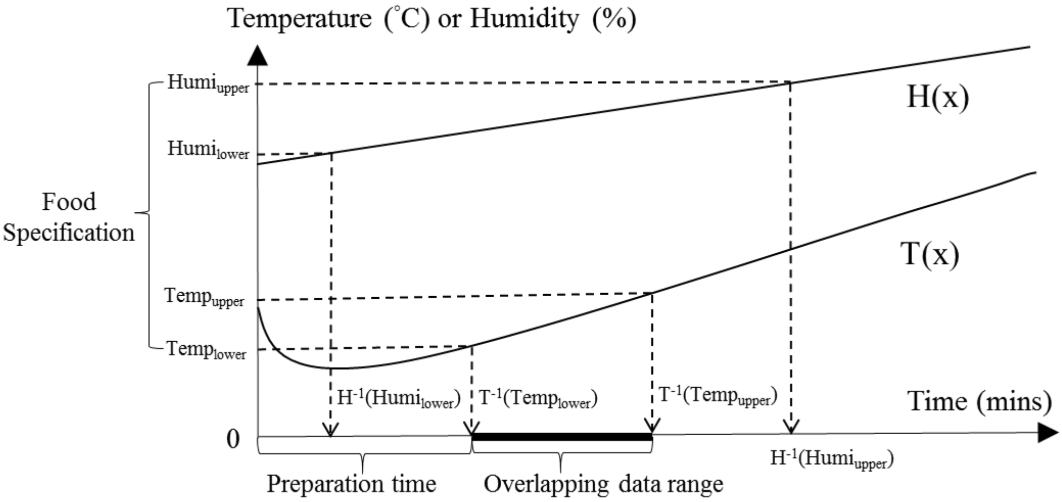


Figure 3.13 Rate of change of temperature and relative humidity over time

Table 3.3 Properties of polyfoam box and eutectic plate

	Box internal dimension	Eutectic plate volume	Number of eutectic plates
Level 1	43 × 33 × 23 cm (ESP - 2)	200 ml	1
Level 2	45.5 × 45.5 × 28.5 cm (ESP - 1)	500 ml	2
Level 3	53.5 × 39 × 24.5 cm (ESP - 0)	1000 ml	3

Table 3.4. Full factorial design with orthogonal array of Taguchi L9 (33)

Experiment No.	Factor A	Factor B	Factor C
	Box internal dimension	Eutectic plate volume	Number of eutectic plates
1	ESP - 2	200	1
2	ESP - 2	500	2
3	ESP - 2	1000	3
4	ESP - 1	200	2
5	ESP - 1	500	3
6	ESP - 1	1000	1
7	ESP - 0	200	3
8	ESP - 0	500	1
9	ESP - 0	1000	2

After conducting a set of experiments, the results are then evaluated by the loss function to measure the deviation between the experimental values and the desired values. The loss function is converted into a S/N ratio (η) with three generic quality characteristics, namely STB, LTB and NTB. Since the goal of this module is to maximize the time for meeting the handling conditions, the S/N ratio for the larger-the-better (LTB) quality characteristics is selected, as shown in Equation 3.20.

$$\frac{\mathrm{S}}{\mathrm{N}}\ \text{ratio}\ (\eta) = -10 \cdot \log\left(\frac{1}{n} \cdot \sum_{i=1}^{n} \frac{1}{{y_i}^2}\right) \tag{3.20}$$

, where n is the number of observations, and y_i is the observed time to meeting the handling conditions at the i^{th} experiment.

Consequently, the optimal packaging setting in terms of box dimensions, volume of the eutectic plates, and number of eutectic plates can be determined by selecting the largest positive S/N ratio and the average of means of the overlapping data range from a number of experiments so as to establish the best setting in the passive packaging model for specific perishable food. Therefore, the perishable food can be packed systematically according to the results from the Taguchi method. Eventually, the time for the packaging model to satisfy the handling conditions for perishable food can be changed into the time window of maximum time allowed for transportation for use of optimizing route planning.

3.5.3 Multi-temperature Delivery Route Planning

In this sub-module, mathematical closed-loop delivery route planning with only one depot is formulated by considering the constraints and factors related to capacity, number of vehicles, customer locations, service time window, recycling of eutectic plates, and cooling time window. The proposed delivery route formulation is designed for handling the parcels with multi-temperature criteria. As the food products have been packed by using cold chain passive packaging, as described in Section 3.5.1, the maximum time allowed for transportation for each parcel can then be obtained and integrated into the existing VRPs. Compared with the traditional VRPs, the proposed delivery route planning aims at determining the shortest path for completing the e-orders of perishable food by maintaining the food quality during the transportation. Therefore, the maximum time allowed for transportation, which is obtained by the cold chain passive packaging, is important as one of the constraints, and the quality of perishable food can be guaranteed by satisfying the handling conditions individually.

In the proposed delivery route planning, it is assumed that the trucks and vehicles are identical in regard to truck capacity, speed and energy consumption; customer demands and the required products are known in advance. Typically, delivery route planning is formulated to handle the e-orders made in the previous day so that the packing lists and delivery notes can be generated in advance. In addition, the use of trucks requires a certain amount of fixed and variable costs, including installation cost and fuel cost respectively. Also, in the mathematical modeling, a fleet of vehicles starts and finishes delivery at the same depot, which is the e-fulfilment center, and the packed parcels of food are delivered to the end customers. It aims at minimizing the travelling time and distance between various customer nodes conductive to formulating efficient vehicle routing through using a fleet of vehicles. All the notations used in the model are shown in Table 3.5, and the objective function and relevant constraints are shown as follows (Tsang et al., 2018a).

$$\text{Minimize} \sum_{i\in D_o}\sum_{j\in D_0}\sum_{k\in V}[t_{ij}+(C_v L_{ij}+C_f)]x_{ij}^k \tag{3.21}$$

Subject to:

$$\sum_{i\in D_0}\sum_{k\in V} x_{ij}^k = 1, \qquad \forall j\in D \tag{3.22}$$

$$\sum_{i\in D_0} x_{if}^k = \sum_{j\in D_0} x_{fj}^k, \qquad \forall f\in D \text{ and } \forall k\in V \tag{3.23}$$

$$(\sum_{i\in D_0}\sum_{k\in V} t_{ij}x_{ij}^k)\cdot \omega_{bj} \le T_b, \qquad \forall b\in M \text{ and } \forall j\in D \tag{3.24}$$

$$W_k' = \sum_{i\in D_0}\sum_{j\in D_0} d_j x_{ij}^k, \qquad \forall k\in V \tag{3.25}$$

$$\mathrm{W}_f \ge W_k' - \sum_{b\in M} y_{bf} + p_f - M\left(1-x_{0f}^k\right), \forall f\in D \text{ and } \forall k\in V \tag{3.26}$$

$$\mathrm{W}_j \ge \mathrm{W}_i - \sum_{b\in M} y_{bj} + p_j - M\left(1-\sum_{k\in V} x_{ij}^k\right), \forall i\in D, \forall j\in D \text{ and } i\neq j \tag{3.27}$$

$$W_k', \mathrm{W}_f, \mathrm{W}_j \le W_{max}, \qquad \forall k\in V \text{ and } \forall j,f\in D \tag{3.28}$$

$$\sum_{i\in D_o}\sum_{j\in D_0} t_{ij}x_{ij}^k \le S, \qquad \forall\, k\in V \tag{3.29}$$

$$\delta_j \ge \delta_i + 1 - n\left(1-\sum_{k\in V} x_{ij}^k\right), \qquad \forall i\in D, \forall j\in D \text{ and } i\neq j \tag{3.30}$$

$$\delta_i \geq 0, \qquad \forall i \in D \tag{3.31}$$

$$x_{ij}^k, y_{bj} \in \{0,1\}, \forall \mathrm{i}, \forall \mathrm{j} \in D_0 \text{ and } \forall k \in V \tag{3.32}$$

Table 3.5 Notation of multi-temperature delivery route planning

Notation	**Definition**
Sets:	
D	Set of all delivery locations
D_0	Set of all locations including delivery location and depot, $\mathrm{D}_0 = D \cup \{0\}$
M	Set of all products
V	Set of all trucks
Parameters:	
C_f	Fixed cost in using a truck for delivery
C_v	Variable cost for product delivery depended on travelling distance
d_j	Amount of delivery products to customer j, where $\mathrm{j} \in \mathrm{D}_0$
Lij	Travelling distance between location i and j, where $\mathrm{i}, \mathrm{j} \in \mathrm{D}_0$ and $\mathrm{i} \neq \mathrm{j}$
n	Number of customer nodes, where $\mathrm{n} = \lvert \mathrm{D}_0 \rvert$
p_f	Amount of pick-up from customer f, where $\mathrm{f} \in \mathrm{D}_0$
S	Maximum service hour for the distribution services
t_{ij}	Travelling time between location i and j, where $\mathrm{i}, \mathrm{j} \in \mathrm{D}_0$ and $\mathrm{i} \neq \mathrm{j}$
T_b	Maximum transportation duration for product b, where $\mathrm{b} \in \mathrm{M}$
$Wmax$	Maximum truck capacity
Decision variables:	
W_k'	Initial truck load of truck k at the depot, where $\mathrm{k} \in \mathrm{V}$
W_j	Truck load after having served customer j, where $\mathrm{j} \in \mathrm{D}$
x_{ij}^k	Binary variable to decide the truck k travelling location i to j, where $\mathrm{k} \in \mathrm{V}$ and $\mathrm{i}, \mathrm{j} \in \mathrm{D}_0$
ω_{bj}	Binary intermediate variable to show the product b received by customer j, where $\mathrm{b} \in \mathrm{M}$ and $\mathrm{j} \in \mathrm{D}$
δ_j	Intermediate variable to prevent the sub-tours

As indicated in Equation 3.21, the objective of the proposed multi-temperature delivery route planning is to minimize the transportation time and cost occurred in the delivery process. Constraints 3.22 and 3.23 are applied to ensure that each customer node can only be visited once by the same truck during the transportation. In the constraint 3.24, the completion time in delivering the packed parcels is required to be limited by the specific maximum time allowed for transportation, according to the cold chain passive packaging. The definition of the truck load is the sum of the initial load and weight of parcels to be transported, as in constraint 3.25. Also, the change of truck load after visiting the first customer node is defined in the constraint 3.26, which includes the delivery of the ordered parcels and pick-up of the monitoring devices. The above change of truck load can be extended to the whole delivery route formulation, as in constraint 3.27. Moreover, the control of the truck load, which implies the truck load should be less than the maximum truck capacity, is made as in constraint 3.28. Constraint 3.29 shows that the service time windows should be strictly followed to control the total travelling time of the delivery. Constraints 3.30 and 3.31 avoid sub-tours occurring in the delivery route planning formulation, and define the non-negativity for the intermediate variable. Constraint 3.32 shows binary nature of the decision variables.

In order to solve the above mathematical model in an efficient manner, the genetic algorithm (GA) approach is applied to search for the optimal vehicle routing for multi-temperature food distribution, with four major steps, namely (i) chromosome encoding, (ii) population initialization, (iii) fitness function evaluation, and (iv) genetic operations (Davis, 1991). For the chromosome encoding, a chromosome is defined as a sequence of all the customer nodes which represents a binary individual representation, as shown in Figure. 3.14. According to the defined objective function, the decision variable x_{ij}^{k} implies the arc from node i to node j with using truck k. Therefore, the chromosome can be encoded as follows. The first part shows the selected nodes in this routing model according to the defined constraints, while the second part indicates the starting and ending nodes by using the binary number 1. Thus, the vehicle routing planning can be formulated effectively for multi-temperature food distribution in PFEC.

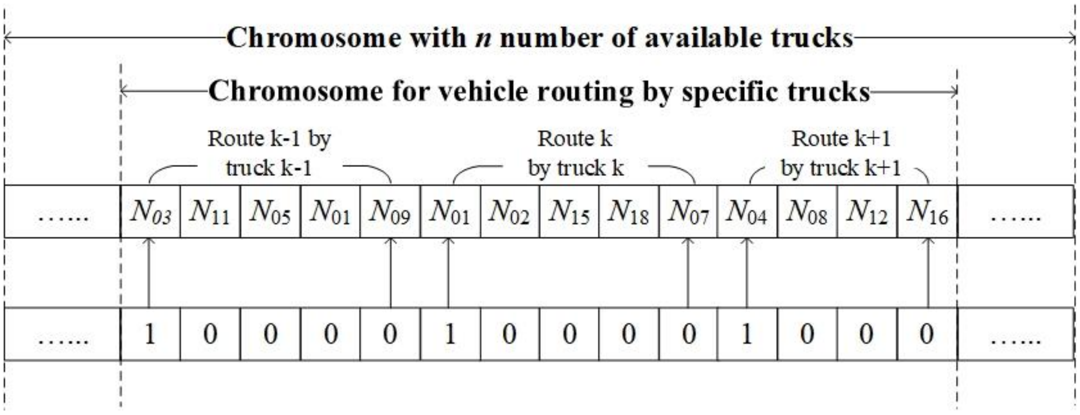


Figure 3.14 Individual representation of delivery route planning problem

3.6 Summary

This chapter presents the system architecture of BIOMES containing three modules, i.e. IoTDM, BDMM and FQMM, to enhance the MTEF process of PFEC. When managing perishable food in e-commerce businesses, the needs regarding passive cold chain packaging, delivery route planning, food quality assessment and food traceability can be addressed by the proposed system. Consequently, the proposed system integrates blockchain and IoT technologies to formulate real-time and reliable data management for recording shipment journeys and food traceability. On the one hand, end customers can access to the data to understand the historical activities and status of the goods to be purchased. On the other hand, the analysis of collected data supports the measures on ensuring food quality, namely cold chain packaging, multi-temperature delivery route planning and food quality assessment. Further, the process between e-fulfilment centers and end customers are tightly monitored by means of IoT and blockchain technologies. Therefore, the product quality and process efficiency can be ensured through the adoption of BIOMES. To apply the proposed system in real-life situations, a roadmap and details of the system implementation are shown in Chapter 4.

Chapter 4. Implementation Process of the BIOMES

4.1 Introduction

This chapter describes the design and development of the proposed system, i.e. BIOMES. A systematic approach on how to develop a blockchain-driven IoT system is provided for supporting the order fulfilment process in PFEC, including developments of blockchain-IoT and decision support functionalities. According to the proposed system architecture of BIOMES in Section 3, three core modules, i.e. IoTDM, BDMM and FQMM, are developed. The entire implementation of the BIOMES is divided into six phases, and the implementation roadmap is shown in Figure 4.1: (i) identification of problems and objectives, (ii) structural formulation of the IoTDM, (iii) structural formulation of the BDMM, (iv) structural formulation of the FQMM, and (v) system implementation and evaluation.

4.2 Phase 1 – Identification of Problems and Objectives

In this phase, the problems and objectives can be identified regarding the MTEF process under the PFEC environment. To present the work done in this phase, three steps are included, namely (i) study of existing MTEF process in PFEC, (ii) problem identification, and (iii) preparation of pilot system development.

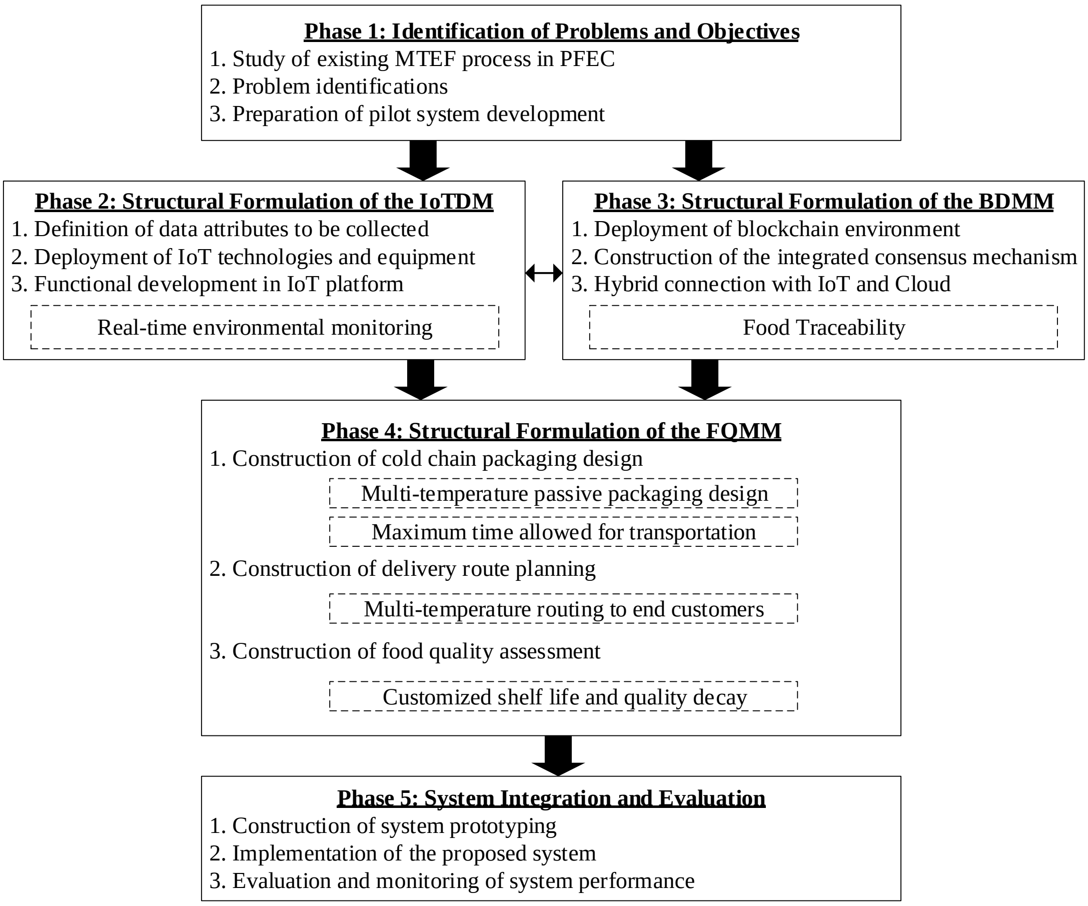


Figure 4.1 Implementation roadmap of the proposed BIOMES

Step 1: Study of existing MTEF process in PFEC

In the first step, the background of the PFEC business is studied through visiting and interviewing of industrial practitioners. After meeting with the staff from relevant companies, the requirements and business models of the PEFC can then be identified and defined such that the differences and values of exploring the perishable food market in e-commerce business can be understood. In addition, meetings with staff from the companies who are doing PFEC business is held to understand the existing

MTEF process in their e-order fulfilment centres. The workflow of the MTEF process, including order receiving, inventory management, picking, packing and delivering, can be identified through site visits to aid investigation of the potential problems and objectives of this project.

Step 2: Problem identification

After assessing the real-life scenarios and companies, the problems can be used to define the project gaps in this project so that it can provide the directions to fill these gaps in this research study. Due to the nature of perishability and customer demand in e-commerce, the MTEF process is different to the existing order fulfilment process for e-commerce transactions. Differing from the e-commerce business for general commodities, the e-fulfilment process needs to maintain the designated environmental conditions for handling food products and to allow the real-time status about the food to be distributed to end customers. Before receiving the food items, the customers can only rely on the information shown in the online retailing platforms about the credentials and descriptive data, and the monitoring and tracking data provided by the e-commerce platforms. If a customer received some poor-quality or deteriorated products, customer confidence to the e-commerce systems, or even the whole PFEC business, can be affected. Therefore, the quality management for food products and supply chain visibility should be improved in the PFEC business to strengthen and consolidate customer loyalty and confidence. The trust between e-retailers, e-commerce platforms and customers can be established to facilitate the trade and interactions. In view of that, the improvement areas can be identified regarding the environmental monitoring, food traceability, and decision support for food quality management. In addition, case studies can be conducted to address the important aspects which are identified and generalized in the PFEC industry.

Step 3: Preparation of pilot system development

To prepare the development of the proposed system, some pre-requisite information is needed to facilitate the system development process. After defining the problems from the literature review and industrial perspectives, the project objectives can be formulated in order to address all the mentioned problem areas by proposing an integrated and effective system. The deployment and implementation of the proposed system should be customized for the PFEC industry, by satisfying the operational process flows and customers' requirements. These can affect the system process flow and the data to be collected and manged in the IoT system. Apart from the technical issues, human factors are considered by regulating and providing adequate training and communication to the staff in the specific companies, so as to prevent human errors and biases in using the proposed system.

4.3 Phase 2 – Structural Formulation of the IoTDM

Phase 2 mainly focuses on the structural formulation of the IoTDM of the BIOMES. The objectives in this phase are to establish real-time environmental monitoring to support the functions of inventory management and to provide environmental mapping analysis in the e-fulfilment areas. There are three steps to achieve the structural formulation, namely (i) definition of data attributes to be collected, (ii) deployment of IoT technologies and equipment, and (iii) IoT system development.

Step 1: Definition of data attributes to be collected

In view of the multi-temperature e-fulfilment process, five major components are involved, including order creation, inventory management, ordering picking, order packing and order delivery, as shown in Figure 4.2. To clearly understand the flow, the Figure 4.2 shows the data attributes concerning in the development of the proposed system with six major aspects, namely customer orders, inventory status, order picking, order packing, delivery orders, and environmental control. The entire e-fulfilment process is activated once customers create their orders in the e-commerce platforms, and their order information is then transmitted to the e-fulfilment centres. To complete the orders, the corresponding products are picked and packed accordingly by satisfying vendor and customer requirements. Overall, the processed orders can be consolidated for last mile delivery from the e-fulfilment centres to end customers. Particularly for the MTEF process, environmental control is essential to ensure the designated level of product quality throughout the entire fulfilment process. Also, the shelf life and quality decay should be also considered to formulate the total monitoring of the food quality. In this project, the environmental monitoring is achieved by deploying the appropriate IoT technologies and systems.

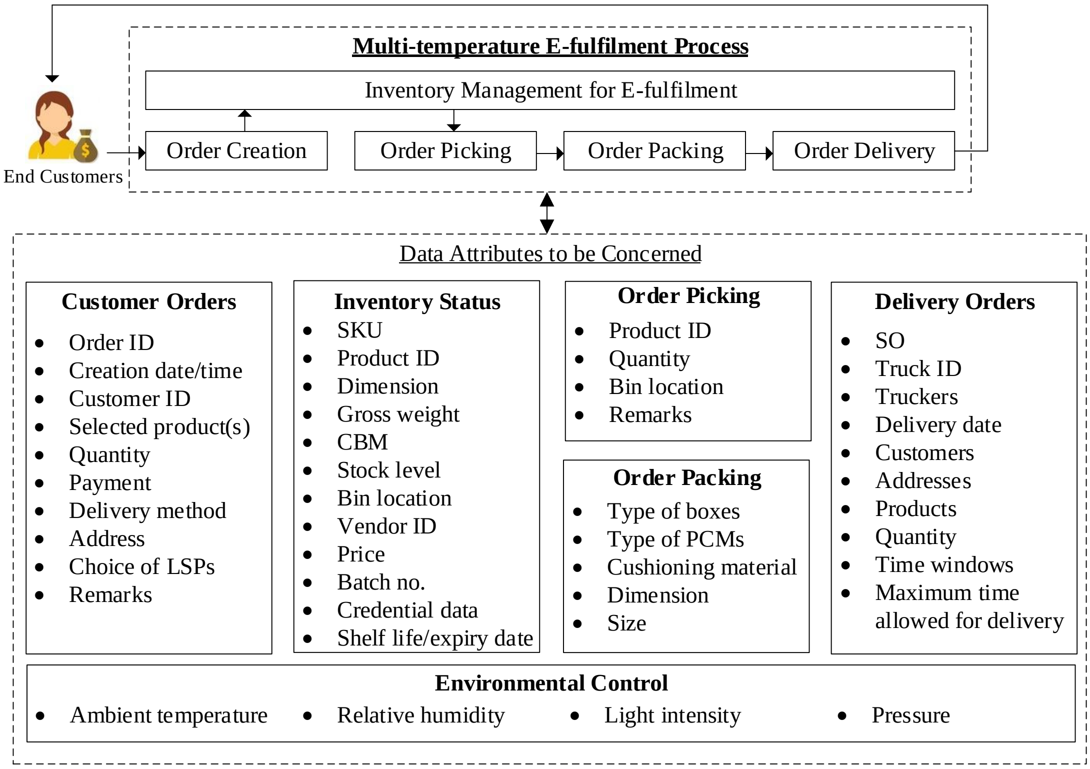
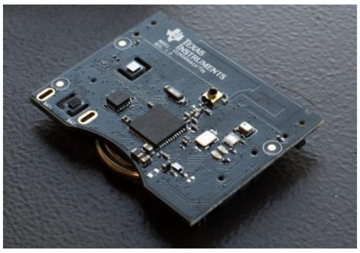


Figure 4.2 Data attributes in the MTEF process

Step 2: Deployment of IoT technologies and equipment

To establish the environmental monitoring, there are two considerations for effectively developing the IoT system, namely (i) selection of IoT devices and (ii) deployment of wireless sensor network. In this study, the sensor nodes and relay nodes should be selected to transmit the data on environmental conditions to the IoT development platform. SensorTag CC2650 is the selected sensor node for data capturing due to its reasonable cost, multiple communication capabilities, and ease of transmission to the IoT development platform. It can be connected to the relay nodes and edge routers using Bluetooth or 6LoWPAN, so that it is suitable to deploy the environmental sensor network in an indoor environment, such as in storage facilities. On the other hand, SensorTag CC3200 is selected to be the sensor node for data capturing in an outdoor environment, for example the last mile delivery. It can be connected to portable Wi-Fi enabling 3G/4G/LTE transmission to access the cloud and IoT services. Table 4.1 shows the details and differences between Sensortags CC2650 and CC3200 to assist the decision-making for the use of IoT technologies. In summary, they are used to develop indoor and outdoor environmental monitoring, respectively, to tightly control the environmental conditions throughout the entire e-fulfilment process.

Table 4.1 Specifications of the selected sensor nodes

Details	**SensorTag CC2650**	**SensorTag CC3200**
Figure of sensor node		
Operating frequency	2.4-GHz RF devices	WLAN 2.4Ghz for channel 1 to 11
Sensing devices	3-axis gyroscope, 3-aixs accelerometer, 3-axis magnetometer, temperature sensor, thermopile sensor, pressure sensor, humidity sensor, light sensor	
Use of battery	One CR2032 coin cell	Two AAA batteries
Accuracy of temperature readings	±1°C (-40°C to 125°C)	±1°C (0°C to +60°C) and ±1.5°C (-40°C to +125°C)
Accuracy of humidity readings	±3%	±3%
Wireless communication protocols	Bluetooth, 6LoWPAN and ZigBee	Wi-Fi

After confirming the sensor nodes and relay nodes, a deployment scheme for the environmental sensor network is then needed in the storage areas. By considering the deployment scheme in Section 3.3.3, the model and objective functions are formulated, and solved by using the proposed MTKGA, as shown in Table 4.2. The pseudo code shows the procedures and mechanisms of the proposed MTKGA in the implementation. The optimization solution and the optimal parameter settings can be obtained simultaneously to locate the best set of pareto solutions to address the deployment problem. The number of variables is dependent on the sum of the numbers of maximum possible sensor nodes and relay nodes in the environment. In return, the pareto-solutions can be obtained for decisions on the optimal settings of the IoT deployment scheme. For the palletization and truck-level monitoring, the SensorTag CC3200 can be simply applied to the items for conducting environmental monitoring.

Apart from the features of the sensor nodes, the sensor calibration is also essential to enhance the sensor performance by reducing structural errors, which refers to the differences between expected output and measured output, in the sensor network. The sensor calibration is followed by the cross-calibration scheme to examine the outliers and to measure the noise from the surrounding environment (Royapoor and Roskilly, 2015; Can et al., 2016). First, the connection between the sensor nodes and relay nodes can be examined by controlling the received signal strength indicator to ensure the connectivity. Due to the constraints of the facility infrastructure, the connectivity of sensor nodes should be investigated before the installation. Second, the structural errors can be modelled in the facilities through the evaluation of the differences between the expected and measured readings. Subsequently, the modelled structural errors can be considered in the formulation of the sensor network to improve the data accuracy and trustworthiness.

Table 4.2 Pseudo code of the proposed MTKGA

Algorithm 1 Multi-response Taguchi-guided K-means Genetic Algorithm

```
1: Initialize crossover rate $c$, mutation rate $m$, population size $p$, and cluster number $k$
2: Formulate Taguchi orthogonal matrix $T = \{c_l, m_l, p_l, k_l\}$ with parameter level $l \in L$
3: switch ($c_l, m_l, p_l, k_l$)
4:   case $c_l \leftarrow c_1, m_l \leftarrow m_1, p_l \leftarrow p_1, k_l \leftarrow k_1$
5:     Generate $s$ chromosomes with $g \leftarrow n+m$ genes randomly
6:     for ($i$ from 1 to s) do
7:  Evaluate fitness values $x_F = \{f_1, f_2,\ldots,f_p \mid f_j \in \mathbb{R}\}$ and constraints $x_C = \{con_1 \wedge con_2 \wedge \ldots \wedge con_q\}$ of chromosome $s_i$
9:     end for
10:    Initialize $k_1$ coordinates ($x_{Fint}$, $x_{Cint}$) of k centroid randomly
11:           Measure Euclidean distance: $d \leftarrow$ dist[($x_F$, $x_C$), ($x_{Fint}$, $x_{Cint}$)]
12:    Formulate $k_1$ clusters with the closest chromosomes
13:    while not(termination$_1$) do
14:           Calculate new $k_1$ centroid coordinate: ($x_{Fnew}$, $x_{Cnew}$) $\leftarrow(\overline{x_F}, \overline{x_C})$
15:           Formulate $k_1$ clusters with the closest chromosomes
16:           while (cluster size $\leq p_1$) do
17:                  Add additional chromosomes $s_{add}$ to the existing pool s
18:                  Evaluate its fitness value, constraints and Euclidean distance
19:                  Assign them to the closest centroid
20:           end while
21:    end while
22:         Get the initial population with the best average fitness values among $k_1$ clusters
23:    While not(termination$_2$) do
24:           Genetic operations of selection, crossover and mutation
29:           Measure the percentage change of spread: $(sp_i-sp_{i-1})/sp_{i-1}$
30:           Record iterations: iter $\leftarrow$ iter + 1
31:    End while
32: Repeat for steps 4 to 31 according to T
33: Calculate and normalize SN ratios: $\omega_{ijk}$
34: Obtain the optimized parameter setting in MOO
```

Step 3: Functional development in IoT platform

To develop the IoT system, the environment and services of the IBM Cloud are selected due to the advantages of cost, information security, device management, and application program interface (API) capability. As shown in Figure 4.3, the IoT development in the IBM Cloud has three components, i.e. SDK for Node.js, Internet of Things Platform and Cloudant/MySQL. The sensor devices can be connected to the Internet of Things Platform by using some machine-to-machine protocols, such as MQTT and IBM registered services, while the entire system, including front-end (HTML, JavaScript and CSS) and back-end (Python and JavaScript) developments, can be conducted in the Node-RED environment which is a flow-based programming editor. The sensor devices can be effectively managed in the IBM Cloud by maintaining their configurations, such as token value and broker information. To effectively manage the collected data, MySQL or Cloudant can be used, depending on the system requirements. The real-time data can be shown in the system dashboard, while the data can be stored in the cloud database in a real-time or a regular manner, depending on the system requirements by customers.

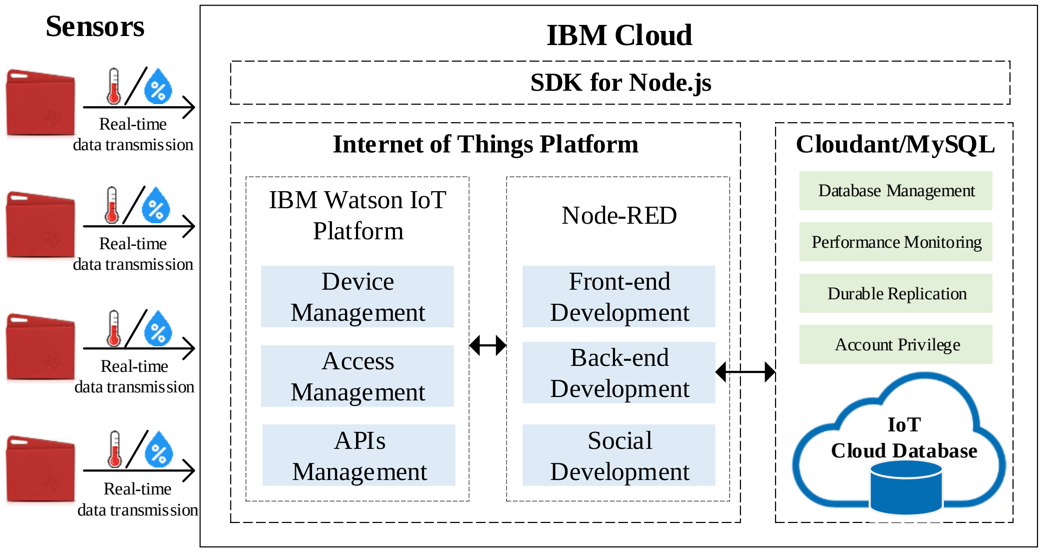


Figure 4.3 System flow between sensors and IBM Cloud

4.4 Phase 3 – Structural Formulation of the BDMM

The above IoT technology deployment provides the real-time data capturing and management, but the functions on the creation of network synchronization and system reliability in the supply chain network are inadequate. Phase 3 is designed to show the structural formulation of the BDMM in addressing the aforementioned concerns so as to establish adaptive and secure food traceability for PFEC. Also, the integration process of blockchain, cloud computing and IoT is illustrated. In the structural formulation, there are three steps, namely deployment of blockchain environment, construction of the integrated consensus mechanism, and hybrid connection with IoT and Cloud.

Step 1: Deployment of blockchain environment

In the IBM Cloud environment, the system module related to blockchain mechanism, including the interplanetary file system (IPFS), is created in the applications, and IBM blockchain can be used to manage the data which need to be stored in a secure and reliable manner, particularly for the functions of food traceability. The data block structure is **block** = {*index*, *timestamp*, *data (associated IDs)*, *hash*, *previous_hash*, *nonce*}, where the first data block, i.e. genesis block, has zero values in the index and previous hash. Also, the hash value in the study is generated by the algorithm of SHA-256 within the family of SHA-2. Though the method of SHA-256, the messages and data collected by the proposed system can be converted into a string with a 256-bit length. It is a one-way algorithm to process the messages and data, and the entire process cannot be done reversely. Moreover, blockchain users or corresponding machines can upload the data by using asymmetric encryption to ensure the security of the payload of data.

Step 2: Construction of the integrated consensus mechanism

After uploading the data in the blockchain network, the data block needs to be validated by the users in the entire distributed network. With the adoption of the proposed PoSCS, the longest chain rule and customized calculation of weights are applied in the supply chain network. The former means that the valid blockchain and data chain can only be the longest chain in the network as the most effort and work have been done to validate the data. It prevents data tampering and replacement of the validated data in the blockchain. The latter refers to the proposed consensus mechanism, PoSCS, through considering three major factors: the involved transit time, stakeholder assessment, and shipment volume. To construct the PoSCS, the average transit time for each supply chain stakeholder in the specific food supply chain should be evaluated to investigate the duration of holding ownership of the food products.

Also, the stakeholder assessment is applied to investigate the potential value obtained by the supply chain stakeholders after adopting the food traceability and blockchain applications. The supply chain stakeholders, having a higher score in the assessment, should contribute more on the block forging work to sustain the blockchain network. Lastly, due to ever-changing and fiercely competitive business environment, the shipment volume in a given period time is also considered in order to adjust the weights of the supply chain stakeholders. By integrating and consolidating all the above factors, the consensus mechanism can be effectively formulated to facilitate and sustain the block forging process. Therefore, the blockchain mechanism can be deployed and implemented to satisfy the requirements in food traceability.

Step 3: Hybrid connection with IoT and Cloud

To achieve the light-weight and vaporized characteristics in the blockchain-driven system, hybrid development with IoT and cloud technologies is needed. Figure 4.4 shows the overall structure of the proposed blockchain mechanism used in this project. On the one hand, the data to be forged in the blockchain is an associated ID, which is referred to the entire data row in the cloud database. By doing so, the time and resources used in block forging process can be eliminated, and the capacity and system memories used for the blockchain-driven system can be minimized. The collected data regarding food traceability are managed in the centralized cloud, where the data are protected by the enterprise-level security protocols and firewalls. On the other hand, the life cycle of the blockchain for food traceability is defined in this study from the creation of the genesis block to the ending block, and thus the entire blockchain chain for a supply chain life cycle is vaporized to the cloud for centralized management. The computational load and resources for sustaining and maintaining the blockchain can be released for coming parts of the data chain. Therefore, the hybrid development between the blockchain, IoT and cloud technologies can enhance the system adaptability and practicality of food traceability in the perishable food industry.

4.5 Phase 4 – Structural Formulation of the FQMM

In Phase 4, the structural formulation of the FQMM is presented to achieve three major decision-support functionalities in the proposed system, namely (i) cold chain packaging design, (ii) multi-temperature delivery route planning and (iii) customized food quality assessment.

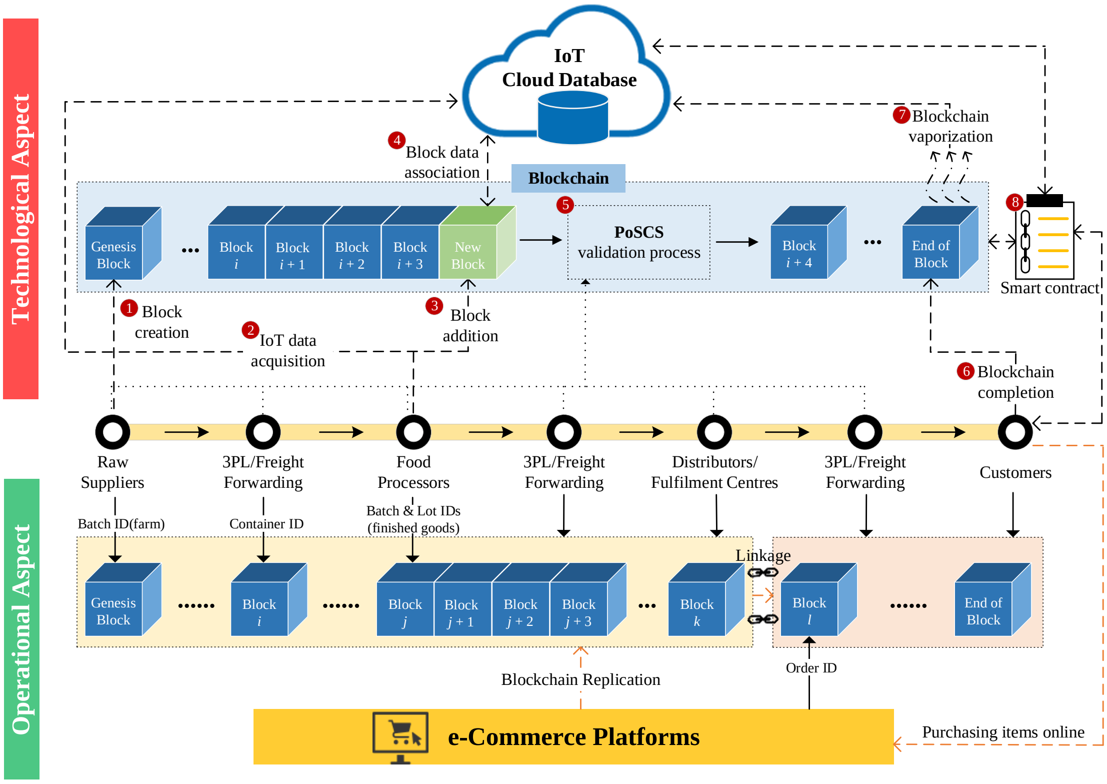


Figure 4.4 Structure of the proposed blockchain mechanism

Step 1: Construction of food quality assessment

Apart from achieving the effectiveness of material flow in the MTEF process, the food quality assessment is also important for providing the relevant information to the end customers to assess the products to be purchased and received. In the food quality assessment, fuzzy logic is adopted to customize the food shelf life and quality decay by considering the environmental conditions during the handling process, sensory scores and transit time. Interviews with the domain experts from the case companies should be conducted to formulate the membership functions of input and output parameters. Moreover, the linguistics relationship between input and output parameters is also established in the form of IF-THEN rules, and stored in the knowledge repository for the future use of fuzzy inference engine. The proposed fuzzy logic approach provides a generic method to customize the food shelf life and quality decay for the coming batch of perishable food items. When the input parameters are collected, the fuzzy logic approach can be operated to generate evaluation of the output parameters, including the percentage change of shelf life, rate and order of quality decay. This give a relatively accurate figure to the end customers so as to understand the food quality at the various stages in the e-fulfilment centres and last mile delivery.

Step 2: Construction of cold chain packaging design

To control the perishability of food products from the perspective of material flow, cold chain packaging is essential to protect and provide a suitable environment to the food products during the process from leaving the e-fulfilment centres to reaching the end customers. To examine the optimal packaging settings, DoE of the Taguchi method is applied to establish an orthogonal array for the experimental studies, where the effort to examine the effect by using various combinations of packaging materials can be minimized. After gathering all the experimental results followed by the orthogonal array, the result analysis can be conducted to obtain the main effects of the signal-to-noise ratios on the corresponding factors. The parameters are then selected by having the most positive signal-to-noise values, while the maximum time allowed for transportation, which is essential information to modify the delivery route planning, can be obtained. Overall, the customized cold chain packaging can be formulated to specific kinds of food, and the time for last mile delivery can be constrained.

Step 3: Construction of multi-temperature delivery route planning

Following by the aforementioned experiments, the maximum time allowed for transportation can be formulated, and is a piece of important information affecting the delivery route planning in the last mile delivery process. By integrating with the capacitated vehicle routing problem, the travelling distance can be minimized to complete all the e-orders for multi-temperature products, while the truck capacity and service time are constrained in the model formulation. The modelled objective and constraints are then optimized by using the GA to search for the optimal solution, and the delivery schedule can be established to decide on the number of trucks to be used and to formulate the routes accordingly.

4.6 Phase 5 – System Integration and Evaluation

To combine the above problem identification and structural formulations of system modules, the proposed system can be eventually implemented as a whole, and its performance and effectiveness are evaluated in a systematic manner. In this phase, there are three phases considered, namely (i) construction of system prototyping, (ii) implementation of the proposed system, and (iii) evaluation and monitoring of system performance.

Step 1: Construction of system prototyping

The formulation of the IoT and blockchain elements is constructed in the IBM Cloud, where the services of the Internet of Things Platform and Blockchain are used. They provide the support of the backend development to manage IoT devices and blockchain data management. For the front-end development, the Node-RED development environment gives the flexibility of various programming languages, including HTML, CSS, JavaScript and Python. The structural formulations of IoTDM, BDMM and FQMM are integrated as a whole to establish the proposed system, namely BIOMES. The system dashboard can thus be established to support the data visualization, information management, and decision support functions, which facilitates the interaction between vendors, e-commerce platforms and end customers in the PFEC industry.

Step 2: Implementation of the proposed system

To implement the proposed system, a case company is selected by re-engineering its operation flow and business models in the PFEC industry. When implementing the proposed system in the industry, the human factor is one of the main factors to be considered because some workers may resist to the change to the existing operational flow even though the changes are beneficial to the entire operations and industry. In view of that, training and structured procedures are provided to let front-line workers and stakeholders for understanding the features and advantages after adopting the proposed system. Particularly for the IoT and blockchain implementation, the most powerful and bargaining power user in the supply chain network should be identified to push the technology adoption, and influence others to apply the proposed system.

Step 3: Evaluation and monitoring of system performance

After implementing the proposed system in the selected case companies, the performance and effectiveness of the system should be evaluated and monitored, by considering the specific key performance indicators (KPIs) regarding the MTEF process. The evaluation dimensions should cover not only the operational effectiveness, but also the customer satisfaction and sustainability of the PFEC businesses. Moreover, regular review of the system performance is critical in order to fine tune the functionalities of the front-end and back-end system modules so as to provide the appropriate user experience and positive effect to the PFEC industry.

4.7 Summary

To conclude, this chapter describes the implementation procedures and major considerations when adopting the proposed system, i.e. BIOMES, including the identification of problems and objectives, structural formulations of three core system modules, and system evaluation. Following the above information, the system can be achieved to address the problems and needs to enhance the MTEF process in the business environment of PFEC. Consequently, the proposed system is then applied in the case companies to investigate its performance, feasibility and values, as discussed in Chapter 5.

Chapter 5. Case Studies

5.1 Introduction

To validate the feasibility of adopting BIOMES for the improvement of the MTEF process in terms of data acquisition, food traceability and quality management measures, two case studies were considered and undertaken in a company which has a unit for PFEC business. The proposed system was implemented in the case company for evaluating the system performance when handling (i) fresh fruit and (ii) meat products. In the two case studies, the implementation of BIOMES can address the needs from the case company, where the proposed system is commonly applicable to the PFEC industry. The performance of three proposed system modules, namely IoTDM, BDMM and FQMM, was investigated. The case studies examined different kinds of perishable food products in the PFEC industry, and thus the practicality and adaptability of BIOMES can be achieved.

5.2 Company Background and Motivation

This section provides a brief company background and motivation for the case studies, and details of the two case studies. The motivation is related to the important aspects for conducting the case studies, which are summarized from the background and existing operations of the case company.

5.2.1 Company Background

With an extended network in U.S., China and Hong Kong, Chevalier AOC Freight Express Holdings Limited (Chevalier AOC) was founded in 1978 as an integrated logistics service provider, with professional services in managing time-critical shipments by means of air freight, ocean freight and road transportation. Chevalier AOC, together with more than 100 (air and ocean) partners, ensures that it has sufficient resources to satisfy customer needs, anywhere in the world. Furthermore, it has a world-wide service network that spans the United States and China, with a corporate commitment to deliver “second to none” services. Abandoning the “one size fits all” approach, Chevalier AOC offers logistics solutions customized to the needs of different sizes and types of companies and customers, and the solutions are designed to meet the current and future needs of the customers. Its success has been established by long-term relationships with both customers and staff members. Also, it focuses on delivering high-quality services in order to outperform to other competitors. To specialize and professionalize the logistics services, Chevalier AOC established eight target segments in the industries: (i) automotive, (ii) aviation, (iii) chemicals, (iv) fashion, (v) pharmaceuticals and life science, (vi) project cargo, (vii) retail and (viii) technology. Dedicated teams and business units are assigned to investigate the industrial situation, and to formulate customized solutions for customers. Moreover, there are five major services provided to customers in addressing the above eight target segmentations: air freight management, sea freight management, road transportation, cold chain management and e-commerce logistics. Regarding the e-commerce logistics, Chevalier AOC created a business unit focusing on the e-commerce business together with the corresponding logistics services. An e-commerce platform is thus established to aim at facilitating trade and logistics services. Its e-commerce logistics services cover business-to-customers (B2C), customers-to-customers (C2C) and business-to-business-to-customers (B2B2C) models. Recently, Chevalier AOC has been committed to developing the e-commerce businesses, covering the perishable food market, selling selected and premium perishable food to end customers. In addition, the e-order fulfilment and last mile delivery are provided along with the establishment of the B2C e-commerce platform. Differing from general e-commerce business, the PFEC business is still under development and exploration so as to formulate appropriate service packages to satisfy the end customers and to build their confidence in purchasing perishable food online. Therefore, integrated e-commerce businesses and solutions are built to penetrate to the perishable food e-commerce market.

5.2.2 Motivation of the Case Studies

In the PFEC business environment, Chevalier AOC tended to explore the market by providing perishable food to the end customers. However, for managing the perishable food e-commerce business, customers are concerned with both the shipment status from the e-fulfilment center to end customers, and with information covering the whole supply chain process, food quality, and environmental excursion management. Existing approaches in the MTEF process, when applied to the case company, have difficulty in dealing with such complex mixtures of TRUs in the traceability process, and in consolidating IoT monitoring information and food quality assessment. Accordingly, supply chain stakeholders and end customers may doubt the reliability, accuracy and efficiency of the MTEF process. Furthermore, solutions for estimating food quality in a cost-effective and timesaving manner are lacking, especially with respect to covering shelf life determination and quality decay modelling. To summarize, customers are mainly concerned with the quality of the received food and information reliability in PFSC, which are the main factors that influence the company's image and future sales performance. In other words, delivering perishable food of poor quality and with poor service causes an increase in the rate of shipment returns, and damages the sustainability of the perishable food e-commerce business. Therefore, the case company requires a reliable and resilient order fulfilment system with the functions of real-time monitoring, an efficient traceability process, and food quality management. To generalize the observations in the industry, the following four important aspects for conducting the case study need to be considered:

a. Effectiveness of data acquisition for environmental monitoring in the MTEF process;

b. Importance of food traceability to identify and track food products in the food industry;

c. Customization of food shelf life and quality decay to reflect the actual food quality status;

d. Discouragement of the development of perishable food e-commerce without effective measures in the MTEF process.

5.3 Case Study 1 – The Deployment of BIOMES on Fresh Fruit

The proposed model (BIOMES) is implemented in the case company to develop a holistic environmental monitoring, food traceability model and food quality management system by means of emerging technologies. As shown in Figure 5.1, the entire implementation of BIOMES in case study 1 is divided into four phases. IoT technologies are applied to perishable foods in a cost-effective manner, according to various types of TRUs. The optimal deployment of an environmental sensor network is also considered for effective environmental monitoring and mapping analysis. In return, a total environmental monitoring system is established to cover the entire supply chain. To track and trace perishable food along the supply chain, an integrated blockchain–IoT approach is applied for activity and milestone tracking. The entire chain stores the activity information and also the data from environmental monitoring so as to create a reliable food profile along the supply chain. The key milestone information is linked to the blockchain to achieve a lightweight and vaporised blockchain mechanism in order to improve the practicality of the blockchain application. Subsequently, the collected data are used to evaluate food quality by means of a fuzzy logic approach for customizing the food shelf life and quality decay. With a reliable source of data acquisition, the accuracy and representativeness of the decision-support functionalities can be improved. The above food quality measurement is the step of data analytics to establish a generic and intelligent method to investigate and visualize the deviation and discrepancy for a batch of perishable food to be handled and sold. All in all, the blockchain-enabled IoT system is developed for enhancing the effectiveness and efficiency of the MTEF process in PFEC business in terms of data acquisition, food traceability and intelligent food quality evaluation.

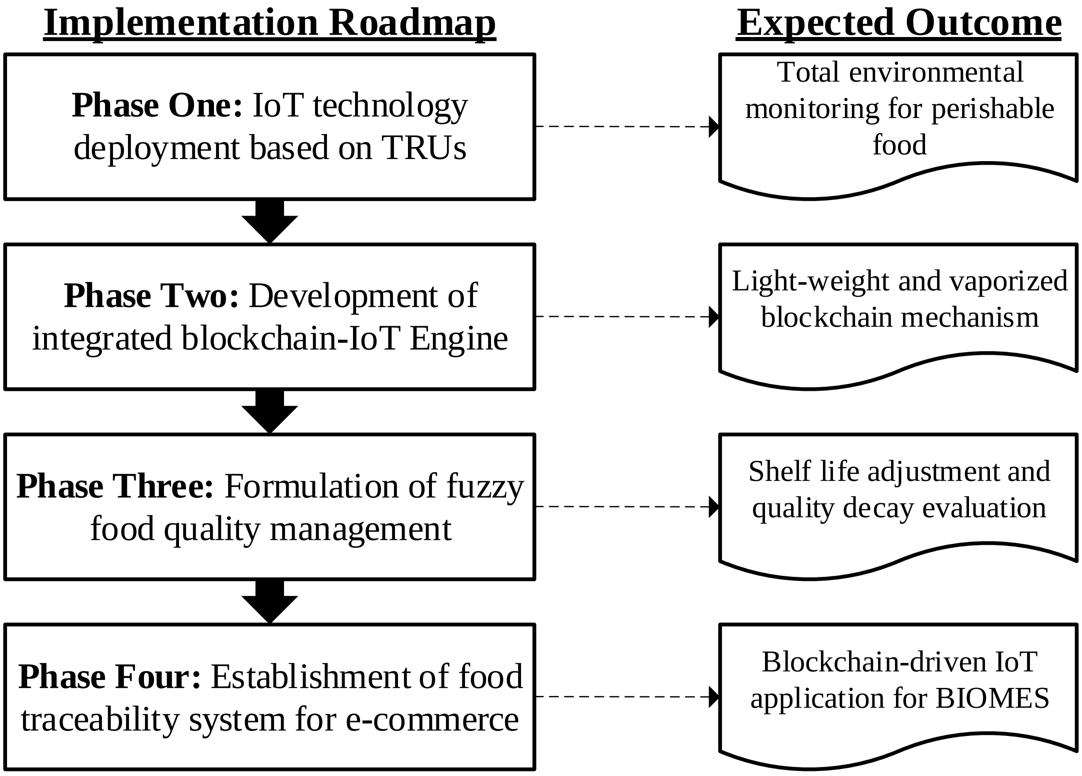


Figure 5.1 Implementation roadmap of BIOMES in the case study

5.3.1 Deployment of IoTDM

In the case company, five stock-keeping units (SKUs) of perishable food, namely fresh fruit in this case study, were selected in the pilot study, all of which were sold on e-commerce platforms. The generic supply chain structure, from raw suppliers to end customers, are summarized in Figure 5.2, and the food was handled at either container-, batch-, or piece-levels. First, when the food was handled at the container-level, the optimal deployment of ESN in a three-dimensional environment was considered and complies with certain temperature mapping requirements, such as WHO TRS961 and CFDA (Tsang et al., 2019). Subsequently, the environmental monitoring and mapping systems were applied in the warehousing facilities. Further, the temperature excursion management for container-level shipments was controlled by using active containers, which provide refrigeration and air conditioning during transportation. Second, when the food was handled at batch-level between the food processing and fulfilment centres, IoT sensors (such as SensorTag CC2650) were used to collect real-time environmental conditions, such as ambient temperature and relative humidity (Wang et al., 2015; Tsang et al., 2018b). The sensors were then connected to edge routers via wireless communication technologies (such as Bluetooth and Wi-Fi) and the collected data were transmitted to IoT development platforms (e.g. IBM Cloud). At batch-level transportation, multi-temperature joint distribution was applied to set up various temperature ranges in the trucks, so that a full truck load in trucks and temperature excursion management can be achieved for effective shipment consolidation (Kuo and Chen, 2010). In an e-commerce business, fulfilment centers play an important role in processing e-orders and for last-mile cold chain logistics, and all the stocks that are ready in the e-commerce platforms are kept and managed in the fulfilment centers. In addition, the fulfilment centers are responsible for performing value-added services, including labelling. The updated food labels contain information on the adjusted shelf life and quality decay (but not food information). End customers can access the food traceability information, covering the source of origin, shipment journeys, batch and lot numbers, and environmental monitoring, via QR codes. For the transportation in piece-level shipments, hybrid and passive cold chain packaging was applied to ensure handling requirements in an efficient method of handling food with palletization. The assignment of various types of packaging materials and eutectic plates are considered to cater for the needs of high flexibility in shipment coordination and temperature excursion management simultaneously. Overall, IoT technologies that are connected to a number of business systems (for example freight management and food information systems), are deployed in the entire life cycle of PFSC. To aggregate the above deployment scheme, the IBM Cloud was selected as the IoT development platform, due to its advantages of cost, information security, device management, and API capability. For the sensor nodes of SensorTags CC2650 and CC3200, the real-time data collected can be achieved using MQTT or IBM registries services, while the entire system (which includes front- and back-end developments) can be conducted in the Node-RED environment. To manage the collected data effectively, MySQL or Cloudant can be used, depending on system requirements, where the former supports the NoSQL and SQL queries and the latter is mainly working with NoSQL. The data to be processed between database and the proposed system are in the form of JSON.

In addition, the IBM Watson IoT platform was used to manage physical devices and APIs, and Node-RED is the development tool to create the system prototype.

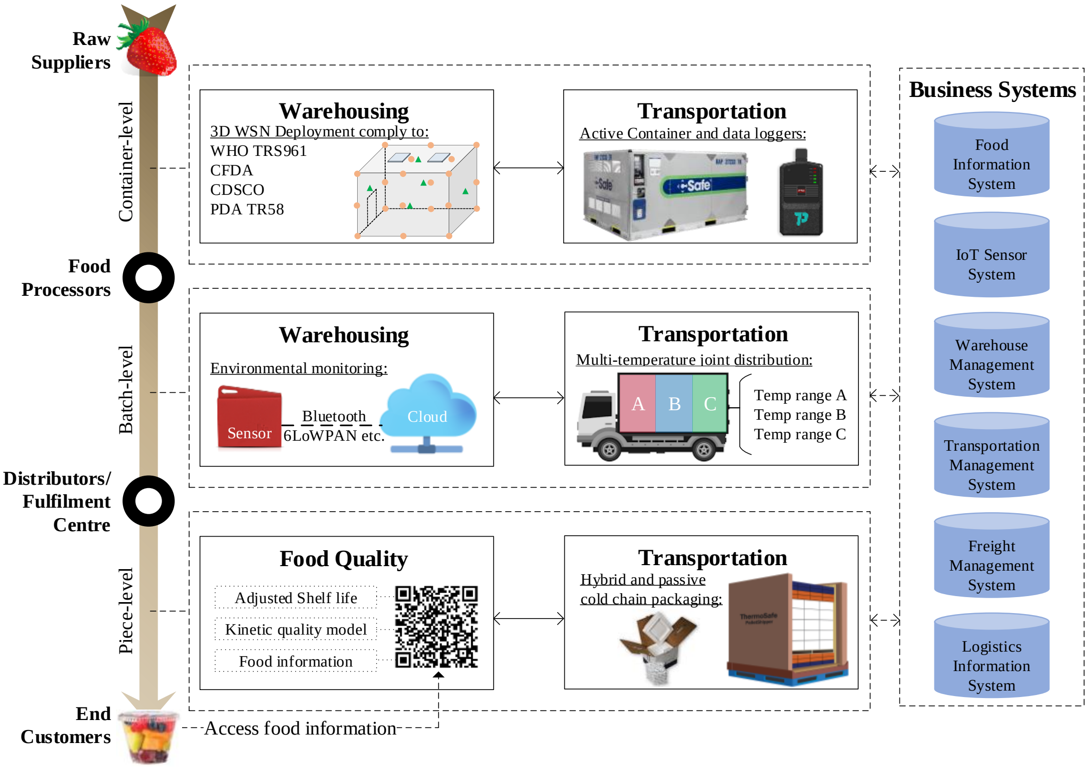


Figure 5.2 Framework of technology deployment in the MTEF process

Particular to the deployment scheme for the environmental monitoring and mapping analysis, one of the storage areas in the e-fulfilment center was selected to implement the proposed deployment optimization problem in IoTDM. Figure 5.3 shows the possible locations for installing the sensor nodes and relay nodes in the selected storage area, where there is one pallet racking used for the bulk storage. In order to evaluate the performance of the proposed deployment scheme, the baseline in terms of the number of used sensor nodes and relay nodes was established, according to the WHO Technical Report Series no. 961 (TRS 961). The criteria for determining the locations of sensor nodes in a 3-dimensional environment is summarized as follows:

For the aspect of length and width:

- Environmental sensor nodes should be placed adjacently within 5 to 10 meters.
- Layout of the area, shelving and products may affect the degree of airflow.
- Sensor nodes should coincide with locations of the perishable food items.

For the aspect of height:

- When the ceiling height is less or equal to 3.6 meters, the environmental sensor nodes should be placed at the high, medium and low levels.
- When the ceiling height is greater than 3.6 meters, the environmental sensor nodes are placed at high and low levels, and some at medium levels should also be considered.

The sensor network deployment from TRS 961 provides certain flexibility to install the sensor nodes and relay nodes in the 3D environment. However, in existing practice, the mapping analysis is conducted on a regular basis, which cannot guarantee the consistency of the environmental conditions. Therefore, the environmental monitoring and mapping should be integrated as a whole to monitor the environmental conditions and to investigate the extreme spots in a real-time manner. According to the baseline situation shown in Figure 5.3, the specifications for an indoor environment is 10m (length) x 10m (width) x 5m (height), where the maximum numbers of sensor nodes and relay nodes to be installed are 50 and 10, respectively. However, deploying all the sensor nodes and relay nodes conforming to WHO TRS 961 is not cost-effective or environmentally-friendly, and requires maintaining a great number of IoT devices. Consequently, the proposed deployment scheme was developed to strike a balance between multiple factors, including cost, coverage, connectivity, fault tolerance, system lifetime and environmental fluctuation. As a result, the appropriate number of sensor nodes and relay nodes can be determined to perform the function of environmental monitoring, and the deployment of sensor nodes can meet the requirements of environmental mapping. Therefore, the environmental monitoring and mapping were integrated in a closed-loop approach, where the environmental monitoring data were inputted to the deployment scheme for adjusting the positions of sensor nodes to be installed.

The optimization problem was then solved by adopting the NSGA-II, as mentioned in Section 3.3.3.4. The NSGA-II approach is capable of solving the above multi-objective optimization problem by searching for the pareto-solution and formulating the pareto-frontier to aid the decision-making process. By using the MTKGA, the optimal parameter settings can be located, while the set of pareto-optimal solutions can be generated. Table 5.1 shows the results of 35 sets of optimized deployment scheme by solving the proposed ESN deployment problem. 35 sets of optimized solutions are not dominated and independent with each other, and thus management level in e-fulfilment centers can make the final decision on the ESN deployment scheme according to the directions and requirements on environmental monitoring and mapping. The criteria for selecting the appropriate deployment scheme are based on the dimensions of six defined objective functions, related to the cost of the sensor nodes and relay nodes, system lifetime, connectivity, environmental fluctuation of temperature and relative humidity.

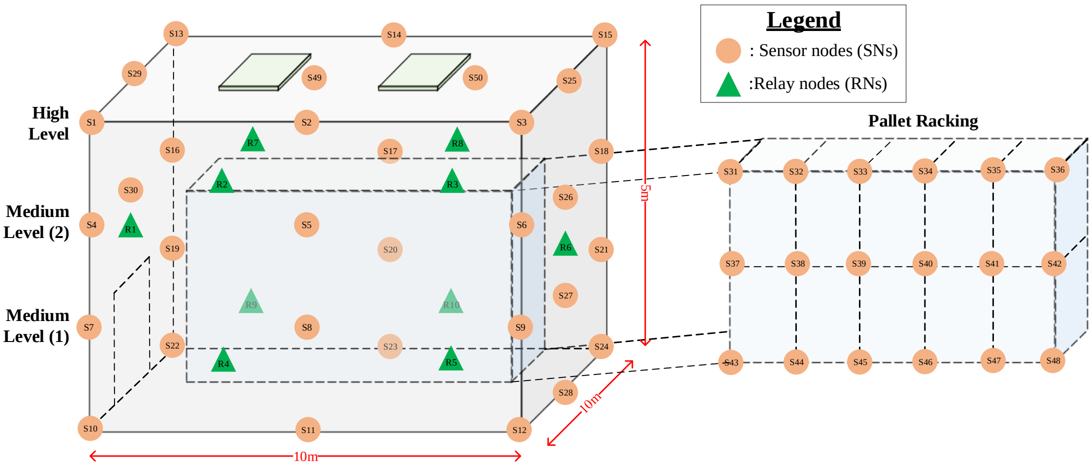


Figure 5.3 Graphical illustration of the storage area in case study 1

Table 5.1 Optimized deployment scheme of ESN in case study 1

Values of the fitness functions						
#	**f(1)_SN**	**f(2)_SN**	**f(1)_RN**	**f(2)_RN**	**f(1)_ES**	**f(2)_ES**
1	-0.9800	-0.8333	-0.9000	-0.6667	-0.9202	-0.2652
2	-0.9600	-0.8571	-0.7000	-0.3333	-1.0013	-0.1547
3	-0.9600	-0.9167	-0.7000	-0.3333	-1.0516	-0.1371
4	-0.9800	-0.6250	-1.0000	-0.3333	-1.0000	-0.2652
5	-0.9600	-0.9167	-0.5000	-0.2000	-1.0000	-0.2308
6	-0.9600	-0.8571	-0.8000	-0.5000	-0.9470	-0.2033
7	-0.9600	-0.9167	-0.6000	-0.2500	-0.6323	-0.2404
8	-0.9200	-0.8750	-0.5000	-0.2000	-0.7996	-0.2423
9	-1.0000	0.0000	-0.9000	-1.0000	0.0000	0.0000
10	-0.9400	-0.7937	-0.7000	-0.3333	-1.0009	-0.1985
11	-0.9600	-0.9167	-0.7000	-0.3333	-0.5280	-0.2533
12	-0.9400	-0.9444	-0.4000	-0.1667	-0.7680	-0.2080
13	-0.9600	-0.9167	-0.6000	-0.2500	-0.6323	-0.2404
14	-0.9800	-1.0000	-0.7000	-0.3333	-1.1008	-0.0374
15	-0.9400	-0.8889	-0.7000	-0.3333	-0.6728	-0.2342
16	-0.9400	-0.8492	-0.8000	-0.5000	-0.8673	-0.2162
17	-0.9200	-0.8571	-0.7000	-0.3333	-0.7667	-0.2297
18	-0.9400	-0.8889	-0.6000	-0.2500	-0.5834	-0.2489
19	-0.9400	-0.8492	-0.7000	-0.3333	-1.0009	-0.1674
20	-0.9800	-1.0000	-0.8000	-0.5000	-0.5798	-0.2409
21	-0.9800	-1.0000	-0.7000	-0.3333	-1.1008	-0.0374
22	-0.9400	-0.7242	-0.9000	-1.0000	-1.0347	-0.1897
23	-0.9200	-0.8452	-0.6000	-0.2500	-1.0007	-0.1965
24	-0.9400	-0.6250	-1.0000	0.0000	-1.0009	-0.1985
25	-0.8800	-0.8621	-0.8000	-0.5000	-0.8058	-0.1991
26	-1.0000	0.0000	-0.9000	-1.0000	0.0000	0.0000
27	-0.9600	-1.0000	-0.3000	-0.1429	-1.0516	-0.1371
28	-0.9600	-0.9167	-0.7000	-0.3333	-1.0516	-0.1371
29	-0.9600	-0.8571	-0.8000	-0.5000	-0.9470	-0.2033
30	-0.9800	-0.8333	-0.9000	-1.0000	-1.0000	-0.2652
31	-0.9400	-0.7540	-0.9000	-1.0000	-1.0009	-0.1985
32	-0.9000	-0.8429	-0.5000	-0.2000	-0.8187	-0.2372
33	-0.9600	-0.9167	-0.7000	-0.3333	-0.5280	-0.2533
34	-0.9200	-0.8750	-0.5000	-0.2000	-0.7996	-0.2423
35	-0.9800	-0.8333	-0.9000	-1.0000	-1.0000	-0.2652

Subsequently, one of the optimized deployment schemes (#2) is shown in Figure 5.4, where the critical sensor nodes and relay nodes can be identified. According to the requirements of the case study, the rest of the deployed sensor nodes and relay nodes can be removed, or changed to other operating modes, such as sleeping mode or activation mode, with longer data transmission intervals. Therefore, the system lifetime can be improved through the adoption of the proposed deployment scheme.

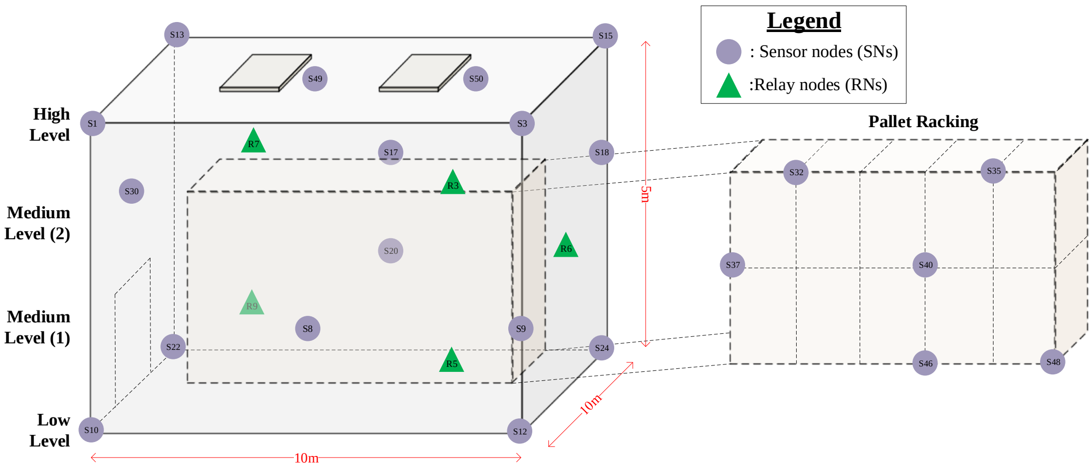


Figure 5.4 Graphical illustration of the optimized deployment scheme (#2)

5.3.2 Deployment of BDMM

Although IoT technologies are deployed effectively in PFSC for improved shipment coordination and temperature excursion management, accurate data and information acquisition are needed to ensure system reliability, adaptability, and scalability. Hence, the blockchain functionalities are enabled in the above IoT applications to strengthen the information acquisition and security in the PFEC industry, as illustrated in Figure 4.5. The figure shows the fusion between operational and technological aspects for adopting blockchain and IoT in the PFEC environment. Practically, the blockchain of the supply chain data has definitive starting and ending sections to express the life cycle of the data chain.

In the technological aspect, the genesis block is created by food suppliers having source of perishable food where unique traceability IDs are assigned to the batches of food for blockchain applications. During various supply chain activities, the IoT data are collected and managed in the centralized database and IoT development platform, such as IBM Cloud, for maintaining business confidentiality and information integrality. Blockchain acts as a sharing tool and reliable method for managing food traceability information, and caters for the needs of various stakeholders in the supply chain. To reduce the computational load and memory usage, the IoT data are managed in the cloud database, while association IDs of the data are generated for storing in the blocks at the step of block addition. The properties of blocks become **block** = {*index, timestamp, data* (*associated IDs*), *hash*, *previous_hash, Rand*}, and SHA-256 is used to encrypt the data and blocks. The added blocks are only valid if the hash value of the block is equal to the output from decrypting the data string (which is previously encrypted by private keys) by using public keys. To validate the added blocks, the

PoSCS validation process is applied to evaluate the values of the supply chain share among all supply chain stakeholders, and to select one of them to forge the blocks in the blockchain. In the selected case scenario, there are six stakeholders to carry and handle the entire process of perishable food e-commerce businesses (α = 0.5). Table 5.2 shows an evaluation of PoSCS among the six selected stakeholders in PFSC. Stakeholder 1 (S1) is selected as an example to demonstrate the calculation steps for obtaining the standardised $S_1(t)$, as shown in Appendix A. The resultant $S_i(t)$ generates the weightings of stakeholders for conducting roulette wheel selection, in order to choose a validator for the block forging process. For the defined milestones for perishable foodstuff, block creation and validation are activated to comprehend the traceability information and the entire food life cycle. At the stage of either point of sales or proof of delivery, the blockchains for particular food products are completed. Subsequently, the entire blockchains are then vaporized to the cloud database to reduce the computational load and release the application memory. All the stakeholders and end customers, who have paid for the products, are obligated to provide relevant information, and can read the traceability milestones and corresponding information via smart contracts. From the operational aspect, the first half of the blockchain (from food suppliers to the fulfilment centres) are built by recording the batch ID (farm), container ID, batch ID (finished goods), and lot ID. The partial blockchain, i.e. the first half, is created according to the batch ID of the specific SKUs of the perishable food, from the production of food suppliers to the stage of e-fulfilment centers. When end customers purchase the food items in e-commerce platforms, the order ID is created, while the first half blockchain is replicated for creating the independent blockchain to the specific orders. The data regarding environmental monitoring and defined activity tracking are then added in the blockchain to complete the traceability records for the use of PFEC businesses. Thus, food traceability for the specific orders (from the source of origin to the end customers) can be achieved effectively and securely.

Table 5.2 Evaluation of PoSCS among supply chain stakeholders in case study 1

Stakeholder	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Factor of transit time (T/T)						
t (in hour)	820	250	1100	210	650	80
Weight in T/T	0.2637	0.0804	0.3537	0.0675	0.2090	0.0257
Factor of stakeholder analysis, where R = [0,5] and α = 0.5						
INF	2	2	3	4	2	5
SAT	3	1	2	2	5	4
INT	5	5	1	2	5	1
DEV	5	1	2	3	1	2
Sum of R	30	6	9	20	30	30
Weight in R	0.24	0.048	0.072	0.16	0.24	0.24
S_i	0.0633	0.0039	0.0255	0.0108	0.0502	0.0062
Std. S_i	0.3961	0.0242	0.1594	0.0676	0.3140	0.0386
Shipment volume for two successive time periods						
V(t-1)	2069	1696	1925	1770	2403	1682
V(t)	1304	1948	2335	1537	3486	1733
Resultant value of PoSCS						
$S_i(t)$	0.0399	0.0044	0.0309	0.0094	0.0728	0.0064
Std. $S_i(t)$	0.2436	0.0271	0.1887	0.0573	0.4445	0.0389

5.3.3 Deployment of FQMM

After the effective data acquisition and management by means of the blockchain-enabled IoT engine, the data can be used for establishing environmental excursion management and real-time environmental monitoring to assist the MTEF process. In the FQMM, the collected and managed data are further applied to strengthen the MTEF process in the aspects of food quality evaluation. cold chain packaging, and delivery route planning.

In the case study 1, five types of food, namely (i) apples, (ii) grapefruit, (iii) mangos, (iv) melons and (v) tomatoes, were selected for the system deployment. For the aspect of food quality evaluation, food shelf life (which is determined by food processors) assumes fixed environmental conditions and transit time on the supply chain activities between the food processors and end customers in traditional practice. However, this cannot reflect the actual situation of food deterioration and spoilage in a fixed shelf life approach. To achieve effective food quality management, a fuzzy logic approach is deployed to determine the dynamic food shelf life and quality decay for perishable foodstuffs. As mentioned in Section 3.5.3, the membership functions (for input and output parameters) and the fuzzy rules should be defined by domain experts in advance. Table 5.3 shows the fuzzy classes, types, and definitions of membership functions for inputs (MKT, MKRH, sensory score and variation of transit time) and outputs (shelf life adjustment, rate and order of quality decay), respectively. Three vertices [v_1, v_2, v_3] represent the formulation of triangular membership functions, i.e. trimf, while four vertices [v_1, v_2, v_3, v_4] express the formulation of trapezoid membership functions, i.e. trapmf. Further, the fuzzy rules for the Mamdani-type inference engine are defined by examining the relevant cases and domain experts, and are stored in the knowledge repository for evaluating output fuzzy sets.

The five selected perishable food products are used to examine the performance of the fuzzy food quality management. At the stage of food distributor and e-fulfilment centre, re-labelling of the QR code labels (as one of the value-added services) is conducted to ensure the appropriate information in the outer packaging. In addition, sensory scores of perishable foods are inspected by a quality control team, by assessing the external appearance, taste, odour, and texture. The fuzzy logic approach is activated when accessing the QR codes by the supply chain stakeholders, particularly end customers. The data regarding MKT, MKRH, sensory score, and variation of transit time are extracted for evaluation of the food shelf life and quality decay model. Table 5.4 shows the results when using a fuzzy logic approach for the five selected food products at the stage of e-fulfilment centres. This illustrates the effect on formulating the dynamic food shelf life and quality decay model in an intelligent manner. The adjustments of food shelf life can be directly applied to the existing shelf life measurements, while the rate and order of quality decay are used to formulate a suitable model to assess the kinetics of food quality changes. The changes of food quality in thermal processing are typically expressed in zero-, first- and second- order reactions.

Table 5.3 Membership functions for fuzzy food quality evaluation for fresh fruit

Parameter	**Abbr.**	**Fuzzy class**	**Membership function**	**Type**
Input:				
MKT (°C)	mkt	Low	[0, 5, 10]	trimf
		Average	[5, 10, 25, 35]	trapmf
		High	[25, 35, 50]	trimf
MKRH(%)	mkrh	Low	[0, 30, 40]	trimf
		Average	[30, 40, 60, 70]	trapmf
		High	[60, 70, 100]	trimf
Sensory score (Scale: 1-10)	R_s	Low	[0, 0, 4, 6]	trapmf
		High	[4, 6, 10, 10]	trapmf
Variation of transit time (hour)	Var_{tt}	Low	[0, 30, 50]	trimf
		Medium	[30, 50, 100]	trimf
		High	[50, 100, 150]	trimf
Output:				
Shelf life adjustment (%)	A_{sl}	Decrease	[-100, -50, 0]	trimf
		No Change	[-50, 0, 50]	trimf
		Increase	[0, 50, 100]	trimf
Rate of quality decay (s^{-1})	R_{qd}	Low	[0, 0.02, 0.04]	trimf
		Medium	[0.02, 0.04, 0.06, 0.08]	trapmf
		High	[0.06, 0.08, 0.1]	trimf
Order of quality decay (unit)	N_{qd}	Zero-order	[0, 0, 1]	trimf
		First-order	[0, 1, 2]	trimf
		Second-order	[1, 2, 2]	trimf

Figure 5.5 illustrates the results of quality decay from fuzzy food quality management for the five selected perishable foods. Under various handling and food conditions, the changes of food quality are different with respect to sensitivity and characteristics.

Table 5.4 Results of food quality evaluation by using fuzzy logic for fresh fruit

	Input parameters				Output parameters		
	mkt	**mkrh**	R_s	Var_{tt}	A_{sl}	R_{qd}	N_{qd}
FF1	8	45	8	35	0.0889	0.036	0.826
FF2	5	36	9	20	0.500	0.093	0.366
FF3	32	65	5	43	-0.289	0.062	1.170
FF4	1.5	38	5	23	0.250	0.020	0.454
FF5	17	39	7.5	40	-0.415	0.047	1.000

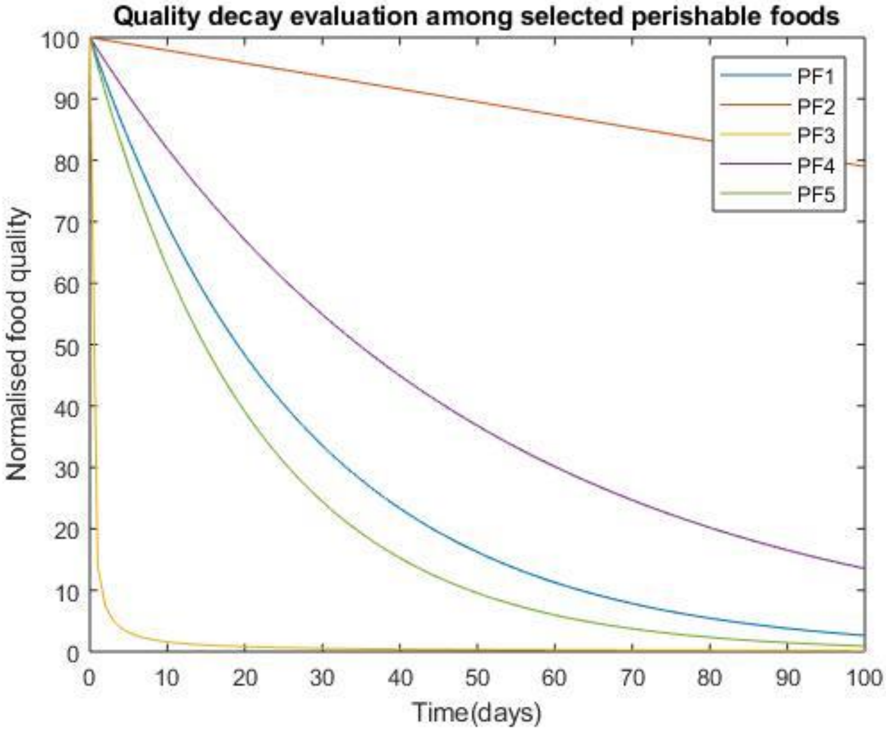


Figure 5.5 Quality decay estimation among perishable foods

Subsequently, the optimal packaging setting of the five selected fruits were examined by conducting a set of experiments according to the full factorial design of the Taguchi method (L_9). Each type of food has its own recommended transport conditions in term of temperature (°C) and relative humidity (%). Table 5.5 shows the specific recommended transport conditions and the corresponding experiment results.

In the experiments, each run was conducted for 4 hours to see the rate of change of temperature and humidity, and this experimental duration was matched to a typical delivery time window of the transportation team in the company. Following the method in the passive packaging modeling module, the cooling durations in minutes were then collected through the experiments, as shown in Table 5.5. Since there is no guarantee that the internal environmental conditions must fit all the recommended temperature and humidity conditions, the value “zero” in the cooling duration is given to imply that the packaging settings do not fit to the products’ handling requirements. However, when applying the higher-the-better approach of S/N ratio in the Taguchi method, the reciprocal value of the square of the cooling durations ($\frac{1}{{y_i}^2}$), as in Equation 3.11, should exist. Therefore, a significantly small numerical value, i.e. 0.001, is used to replace the zero, if the testing packaging design does not fit the specific food, in the cooling duration to maintain the feasibility of the model.

Since the fruits in this study have different recommended transport environmental conditions, the optimal packaging setting by using the eutectic plates and polyfoam boxes can be diversified. Figures 5.6 and 5.7 present the results of the Taguchi-based experiments in the aspects of the S/N ratios and the means of cooling duration for various packaging settings associated with the five types of fruit. The specific optimal packaging settings are determined through the maximum values of the S/N ratios which are of the-higher-the-better type. The highest cooling durations in the packaging model are critical in maintaining the desired product quality for transportation as the maximum time allowed for transportation. Therefore, the best packaging setting for apples were specified as ESP-0 in box internal dimension (η = -25.86; means = 44.56), 1000ml for eutectic plate volume (η = -25.28; means = 48.45), and three eutectic plates (η = -25.28; means = 47.89), so as to maximize the cooling duration for multi-temperature food distribution. Similar to all other fruit, the best packaging setting for grapefruit is referred to ESP-2 (η = 35.41; means = 138.89), 1000ml of eutectic plate volume (η = 26.61; means = 89.22), and two eutectic plates (η = 35.02; means = 128.33); the best packaging setting for mango is referred to ESP-2 (η = 39.01; means = 123.78), 500ml of eutectic plate volume (η = 38.96; means = 124.89), and two eutectic plates (η = 40.88; means = 128.44); the best packaging setting for melons is referred to ESP-1 (η = 32.09; means = 63.78), 1000ml of eutectic plate volume (η = 28.04; means = 68.67), and two eutectic plates (η = 36.06; means = 91.00); the best packaging setting for tomatoes is referred to ESP-1 (η = 44.78; means = 184.44), 500ml of eutectic plate (η = 44.71; means = 182.44), and two eutectic plates (η = 44.96; means = 182.11). The main effects for S/N ratio and mean value for apples are different to the other fruit as most packaging settings in the experiments do not satisfy the handling requirements of apples in term of temperature and humidity. The negative signal-to-noise ratio, which implies that the noise power is greater than the signal power, is not preferable in the Taguchi method. However, due to limited resources and given environment, the generated packaging setting by using ESP-0, three 1000ml eutectic plates, for the apples is considered to be optimal.

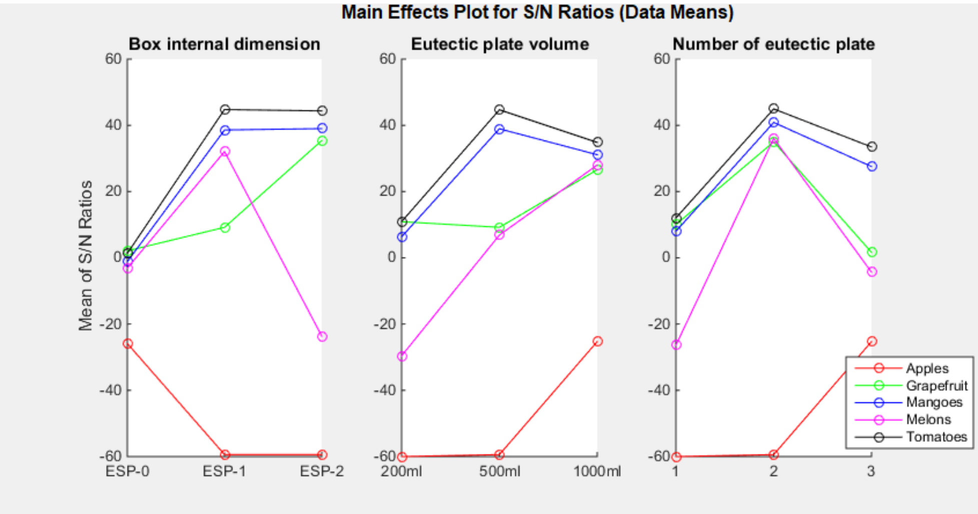


Figure 5.6 Main effect plot for S/N ratios for packaging model

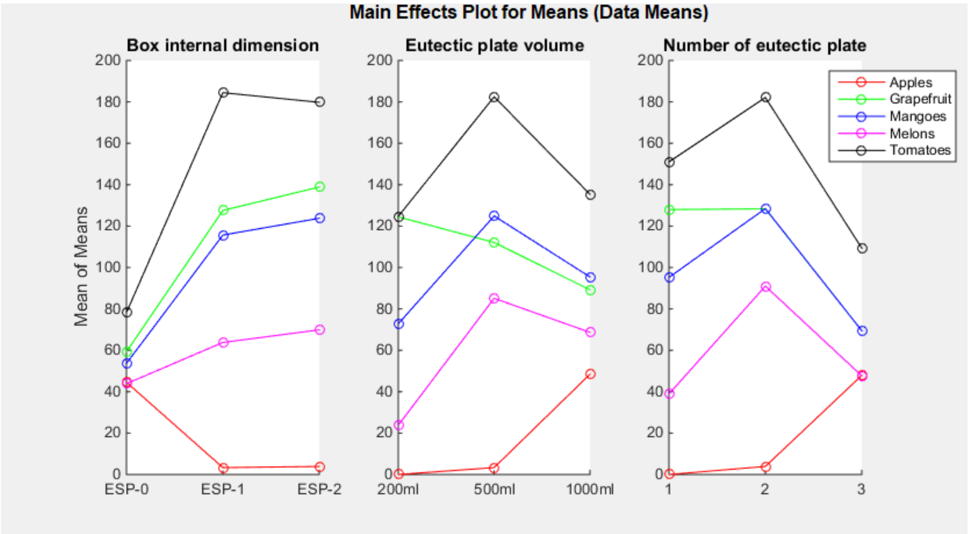


Figure 5.7 Main effect plot for means for packaging model

Table 5.5 Experiment results for five selected fresh fruits

		Apples	Grapefruits	Mangos	Melons	Tomatoes
Temperature		-1 to +4 °C	+10 to +15 °C	+9 to +14 °C	+9 to +12 °C	+7 to +15 °C
Humidity		≤ 95%	≤ 90%	≤ 95%	≤ 95%	≤ 90%
Shelf life		2-7 months	1-2 months	2-3 weeks	2-3 weeks	1-4 weeks
No.	Run	Cooling duration (in mins)				
1	(i)	0	0	0	0	0
	(ii)	0	68	5	0	68
	(iii)	0	45	0	0	45
2	(i)	0	97	132	132	181
	(ii)	0	150	165	120	195
	(iii)	0	143	170	134	200
3	(i)	131	13	4	2	6
	(ii)	120	8	3	3	4
	(iii)	150	10	4	4	5
4	(i)	0	200	139	24	200
	(ii)	0	168	92	20	170
	(iii)	0	150	75	20	150
5	(i)	0	0	90	90	150
	(ii)	0	105	150	150	210
	(iii)	30	0	30	30	120
6	(i)	0	270	120	45	270
	(ii)	0	75	120	120	165
	(iii)	0	180	225	75	225
7	(i)	0	120	60	30	120
	(ii)	0	225	210	120	225
	(iii)	0	144	74	0	144
8	(i)	0	136	72	0	136
	(ii)	0	225	90	30	225
	(iii)	0	153	225	80	225
9	(i)	35	5	64	64	140
	(ii)	0	142	184	170	229
	(iii)	0	100	135	135	174

Table 5.6 summarizes the above optimal packaging settings for the five selected fruits, average cooling duration and required preparation time for the packaging environment. The average cooling duration and required preparation time, which is defined as the shortest time to reach the overlapping data range, were collected in the experiments according to the optimal packaging settings. According to the above results, the cooling durations become the constraint of maximum time allowed for transportation in the route planning model to ensure that the food can be delivered to the customers within the duration of the service time window. In addition, the insulated box should be prepared in advance according to the required preparation time before the food is picked and packed from the storage section. Therefore, the food is prepared for delivering to the customers, and the effective delivery routes should be constructed for the transportation team.

Table 5.6 Optimal packaging settings for five types of fruit

Food type	Optimal Packaging Setting			Cooling duration (min)	Required preparation time (min)
	Box internal dimension	Eutectic plate volume	Number of eutectic plates		
Apples	ESP-0	1000ml	3	143	18
Grapefruit	ESP-2	1000ml	2	183	20
Mango	ESP-2	500ml	2	176	23
Melons	ESP-1	1000ml	2	232	20
Tomatoes	ESP-1	500ml	2	216	26

According to the delivery routing model built in Section 3.5.3, the routing results were obtained by using the GA to minimize the objective function together with the number of defined constraints. In the case company, the transportation schedules and operations are split into morning and afternoon sessions, with 4 hours in each session. Since the company mainly manages the local delivery of premium fruit and vegetables, five 5.5-ton trucks, in which the capacity of each truck is approximately 4-5 pallet spaces with around 6 cubic metres (CBM), are used to complete the customer orders. In order to develop the optimal delivery route, 50 customer locations were selected from the customer pool and scattered on a Euclidean plane of 500x500 km^2. In applying the GA in vehicle routing planning, the system parameters were set as follows: number of iterations = 5000; population size = 150; crossover rate = 0.8; mutation rate = 0.05. The termination criteria of this module were either to reach the maximum number of iterations or to have less than 0.01% improvement in the fitness function value in the last 500 iterations. Figures 5.8 and 5.9 show the results and optimization progress from the delivery route planning function in the FQMM. The optimal delivery route was generated at 2764 iteration with 8798 km total distance. Since the speed of the trucks were assumed to be fixed in this study, the conversion between travelling distance and travelling time can be formulated. Five trucks were fully utilized in transportation activities, considering the constraints of the service time window, cooling time window, and vehicle capacity. Since the GA is a heuristic algorithm in searching for the optimal solution, multiple trials using the same data set and parameter settings are needed to validate the optimality and reliability of the generated delivery results. Table 5.7 shows the results of the total distance and iteration in five different trials for the route planning module. The average total distances for the delivery route and iteration for obtaining the results were 8518 km and 3532 respectively. The difference between the maximum and minimum distance value was around 0.06% so that the routing result from the GA is reliable.

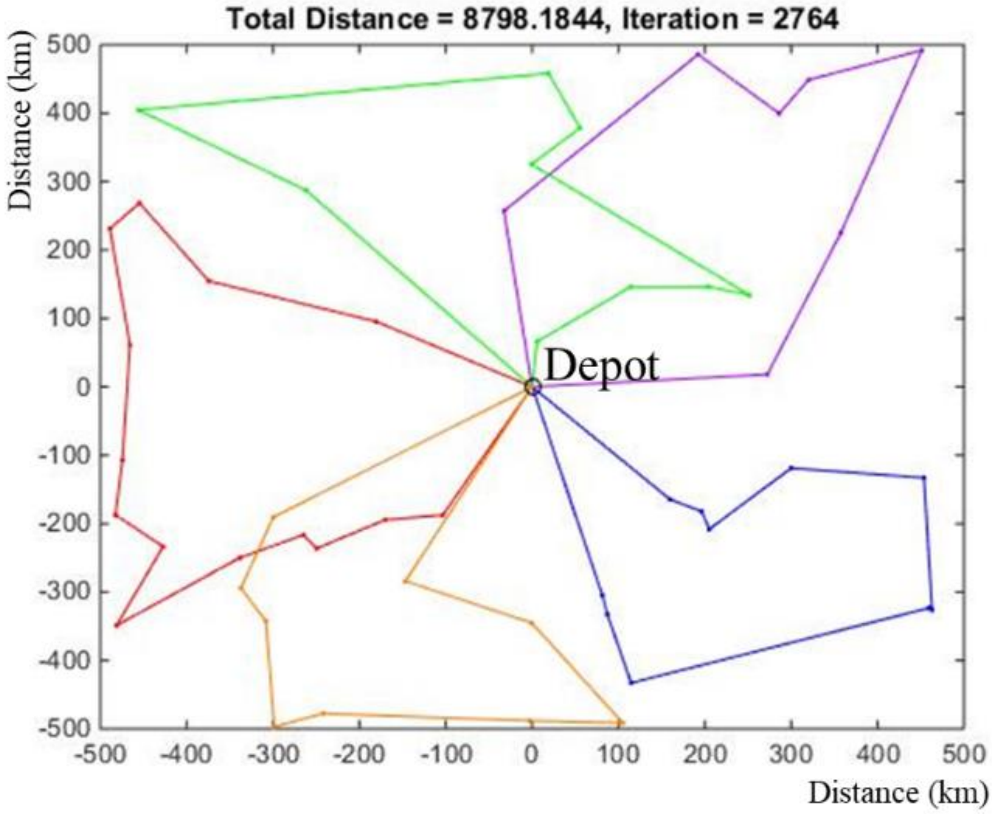


Figure 5.8 Generated delivery route schedules in case study 1

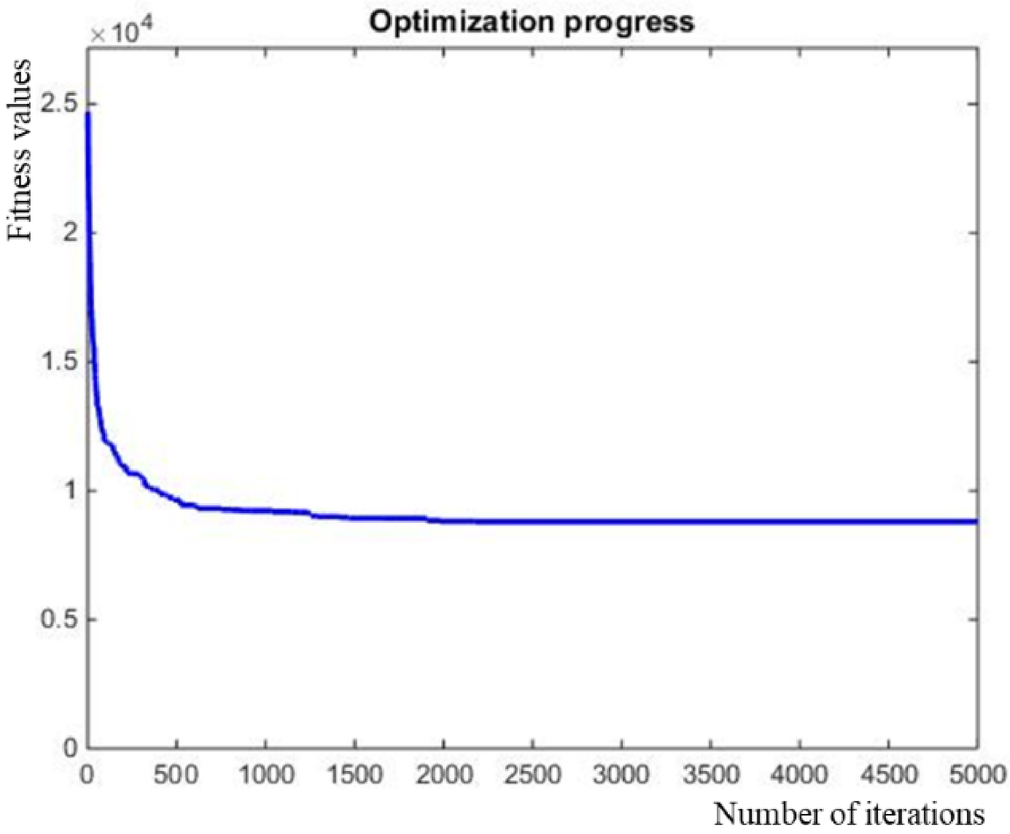


Figure 5.9 Optimization progress with 5000 iterations in case study 1

Table 5.7 Trials for GA-based delivery route planning

Number of trials	Total distance (km)	Iterations for obtaining the results
1	8798	2764
2	8540	2880
3	8321	3932
4	8567	3673
5	8364	4411
Average	**8518**	**3532**

5.4 Case Study 2 – The Deployment of BIOMES on Meat Products

Since the above case study 1 shows the effect and performance of the adoption of the BIOMES on fresh fruit products under the PFEC environment, the generalizability, or so-called genericity, of the proposed system should be investigated. Moreover, the handling specification of meat products and the corresponding supply chain activities are different to the handling of fresh fruit. Therefore, this additional case study by repeating the implementation of BIOMES enables investigation and ensures the functionalities of the proposed system, which contributes the MTEF process in terms of real-time data acquisition, food traceability, and food quality management. The general process flow of the meat supply chain is presented, in Figure 5.10.

The meat supply chain under the PFEC environment can be divided into five major functional groups, namely raw food materials, food processing, B2B distributor, e-fulfilment centre and logistics service provider. Consequently, due to the close proximity in handling fresh fruit, the proposed BIOMES is implemented to investigate the facilitation in MTEF process, as case study 2. Differing to fresh fruits, the sensory evaluation, requirements of environmental conditions, and handling protocols for meat products are different, which can be applied to examine the generalizability of the proposed system.

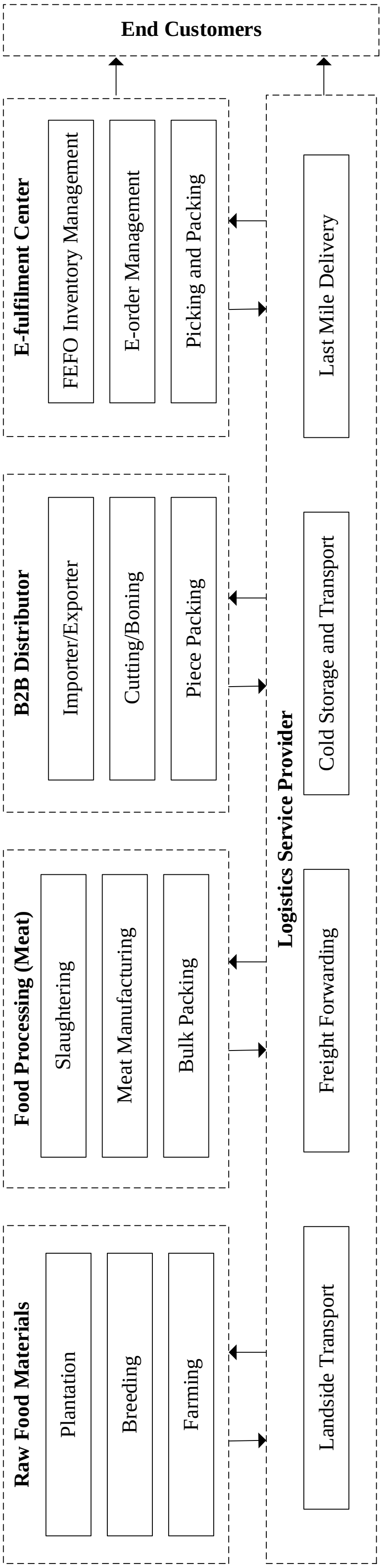


Figure 5.10 Generic meat supply chain under the PFEC environment

5.4.1 Deployment of IoTDM

The deployment of IoTDM mainly covers two functionalities, namely (i) IoT technology adoption along the supply chain and (ii) optimization of ESN deployment. Firstly, similar to fresh fruit, the identification of meat products along the supply chain also relies on various TRUs, such as manufacturing number, batch ID and lot ID. Thus, the same framework can be applied in handling meat products in the container level, pallet-level, and piece-level, as shown in Figure 5.2. The environmental sensor network for indoor environments, sensor attachment, and QR code can be adopted accordingly to monitor the supply chain activities and milestones along the defined supply chain. On the other hand, the deployment of ESN is also optimized in another storage area for handling meat products in case study 2, as shown in Figure 5.11. Based on the WHO TRS 961, the baseline setting for the storage area in case study 2 can be established having four layers: a low level, two medium levels and a high level. The dimensions of the area are 20-meter (length) x 10-meter (width) x 6-meter (height), containing two pallet racking areas. In such an area, 100 sensor nodes and 20 relay nodes were implemented according to the guideline of WHO TRS 961. After applying the proposed MTKGA, the optimized deployment scheme for the ESN was obtained with a set of pareto-optimal solutions, as shown in Table 5.8. Therefore, 20 sets of the optimal-pareto solution were obtained, and the decision-makers in the e-fulfilment center can establish the appropriate deployment of the ESN by considering multiple pre-defined factors. Subsequently, the critical sensor nodes and relay nodes can be identified in the optimization process for achieving environmental monitoring and mapping. Therefore, it is proven that the proposed ESN deployment scheme has flexibility and resilience in regards to the various combinations of sensor nodes and relay nodes.

Table 5.8 Optimized deployment scheme of ESN in case study 2

	Values of the fitness functions					
#	**f(1)_SN**	**f(2)_SN**	**f(1)_RN**	**f(2)_RN**	**f(1)_ES**	**f(2)_ES**
1	-0.4500	-0.6919	-0.9000	-0.9100	-0.6904	-0.1550
2	-0.6500	-0.8415	-0.8000	-0.5000	-0.8224	-0.1354
3	-0.6200	-0.8816	-0.4000	-0.1667	-0.6592	-0.1916
4	-0.5200	-0.7343	-0.9500	-0.9810	-0.7267	-0.1544
5	-0.5700	-0.7452	-0.8500	-0.6733	-0.6772	-0.1551
6	-0.5400	-0.9420	-0.3000	-0.1429	-0.6559	-0.1618
7	-0.7800	-0.8939	-0.0500	-0.1053	-0.6581	-0.1512
8	-0.6100	-0.8889	-0.4000	-0.1683	-0.7282	-0.0942
9	-0.2300	-0.8309	-0.7000	-0.3333	-0.6554	-0.1513
10	-0.6100	-0.6250	-1.0000	-0.0500	-0.7009	-0.1600
11	-0.2800	-0.8631	-0.6000	-0.2500	-0.6760	-0.1541
12	-0.7000	-0.8889	-0.1500	-0.1176	-0.4824	-0.1446
13	-0.7400	-0.8910	-0.2000	-0.1250	-0.4536	-0.1546
14	-0.5700	-0.8760	-0.6500	-0.2857	-0.6916	-0.1393
15	-0.5400	-0.7835	-0.9000	-1.0000	-0.7510	-0.1381
16	-0.6100	-0.6250	-1.0000	-0.0500	-0.7444	-0.1550
17	-0.7200	-0.8929	-0.0500	-0.1063	-0.6391	-0.1418
18	-0.6000	-0.7073	-0.9500	-2.0000	-0.6721	-0.1277
19	-0.5800	-0.8566	-0.5500	-0.2222	-0.6338	-0.1827
20	-0.4700	-0.7865	-0.8500	-0.6667	-0.7094	-0.1410

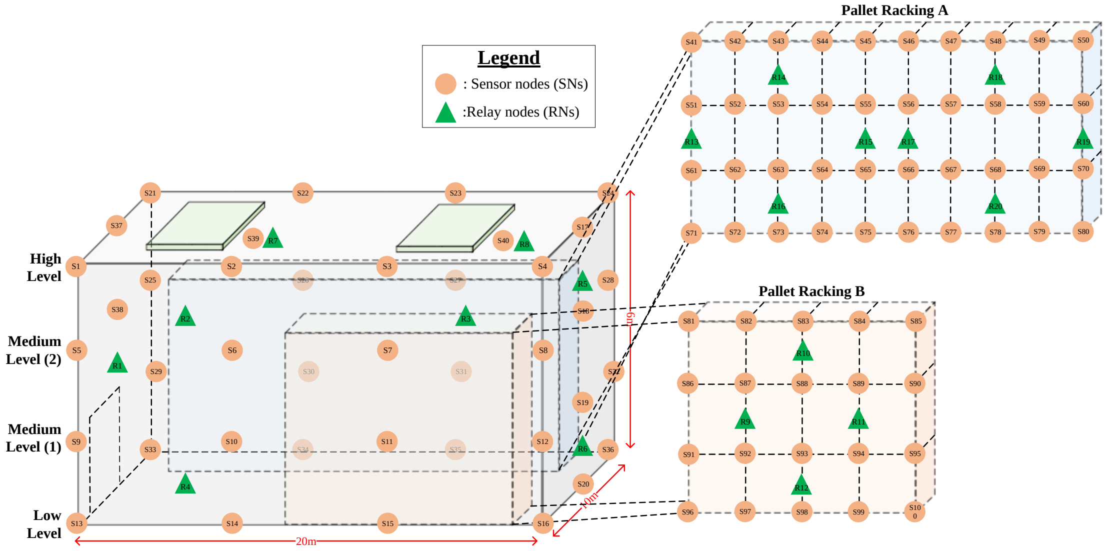


Figure 5.11 Graphical illustration of the storage area in case study 2

5.4.2 Deployment of BDMM

When deploying the blockchain for food traceability, the framework and mechanism follow the illustration in Section 4.4 and the description in Section 5.3.2 for fresh fruit products. The structure of building the blockchain-enabled food traceability follows similar business logic, but the only difference in meat products e-commerce is the number of involved supply chain stakeholders. Similarly, the meat products are traced and tracked by their manufacturing batch and lot numbers along the first half, or called upstream, supply chain activities before entering the e-fulfilment center. After, the order numbers are applied to control and monitor the ordered meat products along the downstream supply chain. In this case study, 10 supply chain stakeholders are involved in the consensus mechanism. Table 5.9 shows the evaluation of PoSCS for the defined 10 supply chain stakeholders. The result of the evaluation shows that the proposed consensus mechanism is able to measure numerous supply chain stakeholders. In return, the method of roulette wheel selection, which is a kind of probabilistic selection, is used to choose the validators for the block forging process. The standardized Si(t) represents the likelihood to be selected for forging a block in the distributed network. According to this mechanism, the parties who have higher power and importance in the supply chain will have a higher chance to be selected as the block validation in the block forging process.

5.4.3 Deployment of FQMM

In the case study 2, the process of the formulation of cold chain packaging, multi-temperature vehicle routing and food quality evaluation is repeated, as in Section 5.3.3. The same methodology is applied to achieve the appropriate quality management for meat products so as to show that the proposed system is feasible for other types of perishable food, but the fresh fruit. Therefore, the deployment of FQMM in case study 2 illustrates the major evidence and results for assessing and comprehending the entire meat products implementation.

Table 5.9 Evaluation of PoSCS among supply chain stakeholders in

Stakeholder	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Factor of transit time (T/T)										
t (in hour)	1995	1856	541	1682	898	1257	1346	725	796	817
Weight in T/T	0.1675	0.1558	0.0454	0.1412	0.0754	0.1055	0.1130	0.0609	0.0668	0.0686
Factor of stakeholder analysis, where R = [0,5] and $\alpha = 0.5$										
INF	4	2	4	5	4	5	5	2	4	2
SAT	4	1	3	3	2	2	5	4	3	3
INT	1	2	2	3	4	4	3	4	2	3
DEV	2	5	1	1	5	5	2	2	4	5
Sum of R	24	7	18	30	36	45	62.5	24	36	24
Weight in R	0.192	0.056	0.144	0.24	0.288	0.36	0.5	0.192	0.288	0.192
S_i	0.0322	0.0087	0.0065	0.0339	0.0217	0.0380	0.0565	0.0117	0.0192	0.0132
Std. S_i	0.1331	0.0361	0.0271	0.1403	0.0899	0.1572	0.2338	0.0484	0.0797	0.0545
Shipment volume for two successive time periods										
V(t-1)	4826	4590	2429	2988	4454	2000	1782	3043	1618	3033
V(t)	2663	4775	1208	2249	3648	1911	3463	3816	4432	2052
Resultant value of PoSCS										
$S_i(t)$	0.0734	0.0376	0.0135	0.1056	0.0736	0.1502	0.4544	0.0607	0.2182	0.0369
Std. $S_i(t)$	0.0600	0.0307	0.0110	0.0863	0.0601	0.1227	0.3713	0.0496	0.1783	0.0301

First of all, in the aspect of food quality assessment, the handling of meat products has some similar factors and criteria to that of fresh fruit, as in Section 5.3.3, namely MKT, MKRH, sensory and transit time. However, to evaluate the sensory score for meat products, the criteria are different to those of fruit products. In the fresh fruit, the sensory score is assessed by considering its colour, flavour, texture, and weight to create a quick evaluation of fruit quality, by returning a sensory score between 1 and 10. Regarding meat products, the sensory score is constituted by considering its colour, tenderness, flavour and juiciness. The fuzzy logic approach for adjusting shelf life and the quality decay model has certain level of flexibility to cater for the various needs of perishable food, such as fresh fruit and meat products. Tables 5.10 and 5.11 show the definition of membership functions and results obtained by using the fuzzy logic approach, respectively. By interviewing the domain experts in the meat supply chain, the fuzzy logic approach can be adjusted and modified in an efficient manner to satisfy the handling of meat products. The collection of membership functions and fuzzy rules for the inference engine can be established by re-interviewing the domain experts and industrial practitioners. According to Table 5.11, the shelf life and quality decay of meat products at the stage of e-fulfilment center can be fine-tuned by considering the impact from the upstream supply chain activities. The customized shelf life and quality decay of the specific batch of meat products can be built and associated with the corresponding batch numbers and SKUs. Thus, the end customers can accurately receive food quality information for the meat products to be purchased and delivered.

Table 5.10 Membership functions of fuzzy logic approach for meat products

Parameter	**Abbr.**	**Fuzzy class**	**Membership function**	**Type**
Input:				
MKT (°C)	mkt	Low	[-25, -10, -5]	trimf
		Average	[-10, -5, 5, 10]	trapmf
		High	[5, 10, 20]	trimf
MKRH(%)	mkrh	Low	[0, 40, 50]	trimf
		Average	[40, 50, 70, 80]	trapmf
		High	[70, 80, 100]	trimf
Sensory score (Scale: 1-10)	R_s	Low	[0, 0, 4, 6]	trapmf
		High	[4, 6, 10, 10]	trapmf
Variation of transit time (hour)	Var_{tt}	Low	[0, 30, 50]	trimf
		Medium	[30, 50, 100]	trimf
		High	[50, 100, 150]	trimf
Output:				
Shelf life adjustment (%)	A_{sl}	Decrease	[-100, -50, 0]	trimf
		No Change	[-50, 0, 50]	trimf
		Increase	[0, 50, 100]	trimf
Rate of quality decay (s^{-1})	R_{qd}	Low	[0, 0.02, 0.04]	trimf
		Medium	[0.02, 0.04, 0.06, 0.08]	trapmf
		High	[0.06, 0.08, 0.1]	trimf
Order of quality decay (unit)	N_{qd}	Zero-order	[0, 0, 1]	trimf
		First-order	[0, 1, 2]	trimf
		Second-order	[1, 2, 2]	trimf

Table 5.11 Results of food quality evaluation by using fuzzy logic for meat products

	Input parameters				**Output parameters**		
	mkt	**mkrh**	R_s	Var_{tt}	A_{sl}	R_{qd}	N_{qd}
M1	-5	90	8	20	0.0006	0.08	0.384
M2	-18	80	9	45	50	0.02	0.435
M3	0	85	6	70	-0.0083	0.02	1

Secondly, regarding the design of cold chain packaging, three different SKUs of meat products are considered and selected from the e-commerce platform in the case company. Also, the eutectic plates used in this case study were changed to anther model, namely pink eutectic gel manufactured by MECALUX logismarket, rather than the typical blue eutectic gel. The white eutectic gel is claimed to handle products between -15°C and -5°C, so that the handling requirements for meat products can be satisfied. The details and experiments to be conducted to the selected meat products are shown in Table 5.12. By using the Taguchi method, the best settings for lamb chops use the combinations of ESP-1 (η = -30.63; means = 62.00), 1000ml of plates (η = 7.17; means = 86.44) and two plates (η = 34.85; means = 93.67). Similarly, the best settings for frozen pork use the combinations of ESP-0 (η = -26.45; means = 26.11), 1000ml of plates (η = -26.04; means = 30.56) and three plates (η = -25.45; means = 28.89). Also, the best settings for deer blade shoulder use the combinations of ESP-2 (η = 42.01; means = 131.67), 500ml of plates (η = 43.00; means = 148.00) and two plates (η = 43.25; means = 156.56). Therefore, the optimal cold chain packaging settings for the selected meat products are summarized in Table 5.13. By using the optimal settings for handling meat products, the duration of handling meat products by using the passive packaging method can be maximized, which can be constituted to the factor of maximum time allowed for transportation in the formulation of the delivery schedule.

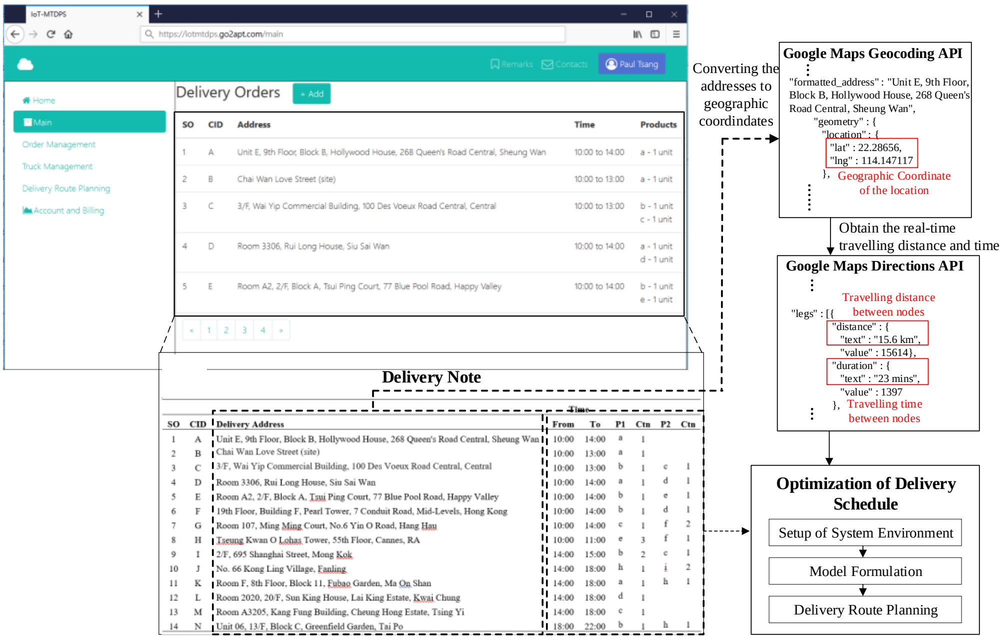
Secondly, the delivery schedule for e-order fulfilment of meat products can be established, in accordance with the route planning model stated in Section 3.5.2. Subsequently, the delivery notes can be formulated by the transportation team to complete the last mile delivery to the end customers. Based on the considered factors and the corresponding maximum time allowed for transportation with respect to meat products, the Google Maps Geocoding API and Directions API are used to collect data on the customer locations and estimated the time between nodes. As shown in Figure 5.12, the process flow in formulating the delivery routes for the transportation team is illustrated. The truckers from the transportation team can complete the delivery order one by one according to the optimized delivery notes. In case study 2, two trucks were finally assigned to complete the e-orders in Hong Kong, as shown in Figure 5.13. One of the trucks was responsible for nine delivery orders in which the customers' locations were nearby in a relatively small area, i.e. Hong Kong Island, while another truck needed to complete five delivery orders in a larger area, i.e. New Territories. The service time window, travelling distance, customer time window and maximum time allowed for transportation of specific food items are balanced in the delivery.

Table 5.12 Experiment results for five selected meat products

		Lamb chops	Frozen pork	Deer blade shoulder
Temperature		-3 to 0 °C	-20 to -15 °C	-5 to 1 °C
Humidity		80-90%	80-90%	85-90%
Shelf life		10-11 days	4-6 months	15-20 days
No.	Run	Cooling duration (in mins)		
1	(i)	0	0	0
	(ii)	0	68	5
	(iii)	0	45	0
2	(i)	0	97	132
	(ii)	0	150	165
	(iii)	0	143	170
3	(i)	131	13	4
	(ii)	120	8	3
	(iii)	150	10	4
4	(i)	0	200	139
	(ii)	0	168	92
	(iii)	0	150	75
5	(i)	0	0	90
	(ii)	0	105	150
	(iii)	30	0	30
6	(i)	0	270	120
	(ii)	0	75	120
	(iii)	0	180	225
7	(i)	0	120	60
	(ii)	0	225	210
	(iii)	0	144	74
8	(i)	0	136	72
	(ii)	0	225	90
	(iii)	0	153	225
9	(i)	35	5	64
	(ii)	0	142	184
	(iii)	0	100	135

Table 5.13 Optimal packaging settings for three selected meat

Food type	Optimal Packaging Setting			Cooling duration (min)	Required preparation time (min)
	Box internal dimension	Eutectic plate volume	Number of eutectic plates		
Lamb chops	ESP-1	1000ml	2	145	16
Frozen pork	ESP-0	1000ml	3	228	22
Deer blade shoulder	ESP-2	500ml	2	250	18



SO	CID	Address	Time	Products
1	A	Unit E, 9th Floor, Block B, Hollywood House, 268 Queen's Road Central, Sheung Wan	10:00 to 14:00	a - 1 unit
2	B	Chai Wan Love Street (site)	10:00 to 13:00	a - 1 unit
3	C	3/F, Wai Yip Commercial Building, 100 Des Voeux Road Central, Central	10:00 to 13:00	b - 1 unit c - 1 unit
4	D	Room 3306, Rui Long House, Siu Sai Wan	10:00 to 14:00	a - 1 unit d - 1 unit
5	E	Room A2, 2/F, Block A, Tsui Ping Court, 77 Blue Pool Road, Happy Valley	10:00 to 14:00	b - 1 unit e - 1 unit

```
⋮
"formatted_address" : "Unit E, 9th Floor,
Block B, Hollywood House, 268 Queen's
Road Central, Sheung Wan",
      "geometry" : {
        "location" : {
          "lat" : 22.28656,
          "lng" : 114.147117
        },
⋮
```

```
⋮
"legs" : [{
          "distance" : {
            "text" : "15.6 km",
            "value" : 15614},
          "duration" : {
            "text" : "23 mins",
            "value" : 1397
        },
⋮
```

Delivery Note

			Time					
SO	CID	Delivery Address	From	To	P1	Ctn	P2	Ctn
1	A	Unit E, 9th Floor, Block B, Hollywood House, 268 Queen's Road Central, Sheung Wan	10:00	14:00	a	1		
2	B	Chai Wan Love Street (site)	10:00	13:00	a	1		
3	C	3/F, Wai Yip Commercial Building, 100 Des Voeux Road Central, Central	10:00	13:00	b	1	c	1
4	D	Room 3306, Rui Long House, Siu Sai Wan	10:00	14:00	a	1	d	1
5	E	Room A2, 2/F, Block A, Tsui Ping Court, 77 Blue Pool Road, Happy Valley	10:00	14:00	b	1	e	1
6	F	19th Floor, Building F, Pearl Tower, 7 Conduit Road, Mid-Levels, Hong Kong	10:00	14:00	b	1	d	1
7	G	Room 107, Ming Ming Court, No.6 Yin O Road, Hang Hau	10:00	14:00	c	1	f	2
8	H	Tseung Kwan O Lohas Tower, 55th Floor, Cannes, RA	10:00	11:00	e	3	f	1
9	I	2/F, 695 Shanghai Street, Mong Kok	14:00	15:00	b	2	c	1
10	J	No. 66 Kong Ling Village, Fanling	14:00	18:00	h	1	i	2
11	K	Room F, 8th Floor, Block 11, Fubao Garden, Ma On Shan	14:00	18:00	a	1	h	1
12	L	Room 2020, 20/F, Sun King House, Lai King Estate, Kwai Chung	14:00	18:00	d	1		
13	M	Room A3205, Kang Fung Building, Cheung Hong Estate, Tsing Yi	14:00	18:00	c	1		
14	N	Unit 06, 13/F, Block C, Greenfield Garden, Tai Po	18:00	22:00	b	1	h	1

Figure 5.12 Process flow of creating delivery note for e-fulfilment

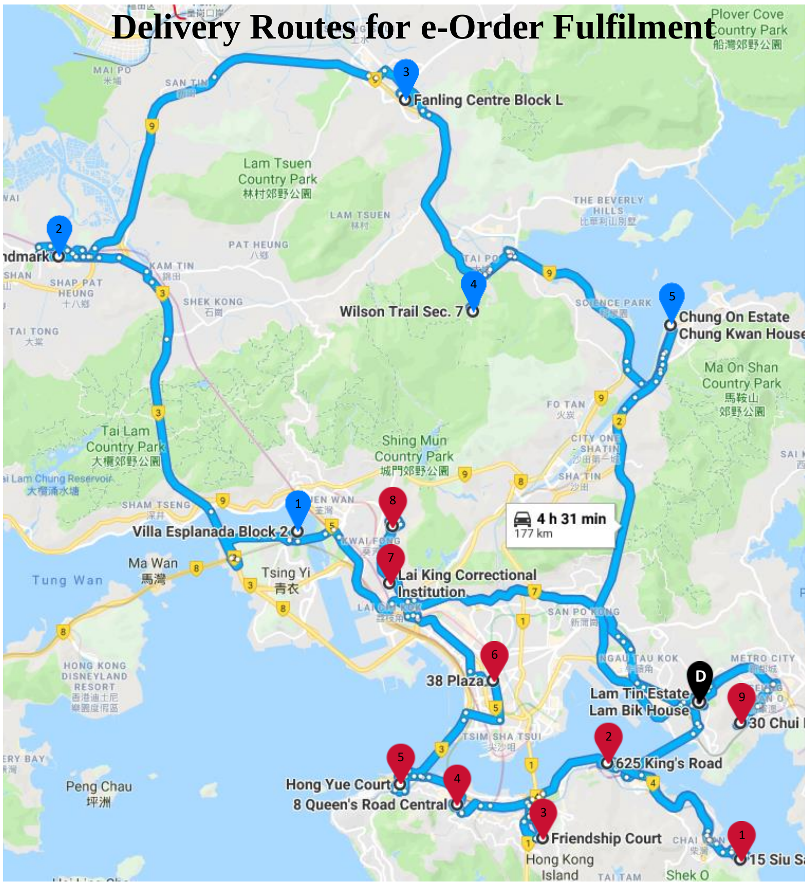


Figure 5.13 Delivery route formulation in the case study 2

5.5 Summary

In this chapter, two case studies were undertaken for the implementation of the proposed system, i.e. BIOMES. To evaluate the feasibility and generalizability of the proposed system, it was necessary to conduct two case studies to validate the scope of the functionalities. In view of that, the proposed system was deployed in two PFEC scenarios, i.e. fresh fruit and meat products. Although fresh fruits and meat products are classified in the category of perishable food which have similar properties and characteristics, the supply chain process, handling requirements, and food quality assessment are different. Through the implementation of the BIOMES, it was shown that the blockchain-enable IoT system, embedding the applied artificial intelligence, enhanced the e-fulfilment process in terms of real-time data acquisition, food traceability and food quality management. Also, the industrial concerns and challenges can be addressed with the aid of the BIOMES. The results obtained from the case studies are further discussed and evaluated in Chapter 6.

Chapter 6 Results and Discussion

6.1 Introduction

After implementing the proposed system, BIOMES, in the case company by conducting two case studies, the feasibility and adaptability can be verified accordingly. In this chapter, the obtained results and findings are then further evaluated and discussed to validate the performance of the proposed system in the area of the MTEF process in terms of real-time data acquisition, food traceability and food quality management. Regarding real-time data acquisition, the performance of the optimization by adopting the proposed MTKGA is examined and compared with other deployment strategies. Moreover, for the blockchain-enabled IoT mechanism, the comparison with the existing consensus mechanism and algorithm is conducted to highlight the values of the proposed PoSCS, while the block forging efficiency with the applied lightweight and vaporized characteristics is also discussed. Lastly, the performance of food quality management is evaluated by using cost analysis to measure the return on investment (RoI) by adopting particular technologies, and sample surveys to analyze the effect on customer satisfaction and operational efficiency. The sample surveys are also aligned with the defined KPIs to truly reflect the actual performance and impact from the proposed system in real-life situations.

6.2 Discussion of System Performance of BIOMES

In this section, the overall system performance of BIOMES in the aspects of IoTDM and BDMM is evaluated and discussed, which are essential in establishing the blockchain-enabled IoT system for facilitating the MTEF process under the PFEC environment.

6.2.1 Performance of Optimization Process in IoTDM

6.2.1.1 Optimal Settings in MTKGA

Through using the multi-response Taguchi method, the time taken in the optimization process and average crowding distance between individuals are considered by applying the STB characteristics in optimizing the parameter settings. This implies that the parameter settings for the GA can obtain minimized computational time and a less crowded region for solution space on the same rank. According to the aforementioned three scenarios for ESN deployment and the multiple responses in the Taguchi method, parameter setting optimization is conducted by measuring the average normalized weights of the SN ratios referred to the proposed MTK. The resultant average normalized weights are generated for each parameter and its corresponding levels, as shown in Table 6.1. The optimal parameter setting is selected by the highest average normalized weights: 0.9897*, 0.9942*, 0.8854* and

0.9870*, among the four levels of crossover rate, mutation rate, population size, and *k* cluster, respectively. Consequently, the optimal parameter settings generated by MTK are as follows: crossover rate *c* is 0.6, mutation rate *m* is 0.1, population size *p* is 50, and cluster number *k* is 4. These are applied in the GA for optimizing the ESN deployment scheme.

Table 6.1 Resultant weights of parameter optimization in MTKGA

Level	Crossover Rate	Mutation Rate	Population Size	Cluster Number
1	0.9696	0.9845	**0.8854***	0.9829
2	0.9874	0.9905	0.8116	0.9841
3	**0.9897***	0.9937	0.7926	**0.9840***
4	0.9793	**0.9942***	0.8063	0.9868

6.2.1.2 Comparison of Baseline, NSGA-II, KGA and MTKGA

A comparative analysis was conducted between the baseline, NSGA-II, KGA, and the proposed MTKGA for solving the problem of three scenarios in ESN deployment. The deployment of the baseline setting was based on WHO TRS 961 to assign SNs and RNs. For NSGA-II and KGA, the default parameter settings from MATLAB were used (0.8 crossover rate, 0.001 mutation rate, and 50 population sizes), with two clusters in the KGA.

The performance measurements among the four methods are based on the normalized generational distance (*GDn*), number of solutions on the pareto-optimal set (*npos*), average number of used SNs (*nsn*), average number of used RNs (*nrn*), and execution time (*texe*), as shown in Table 6.2. It can be seen that in solving the above problem, MTKGA outperforms NSGA-II and KGA in execution time and GDn measurement, with reductions of 13.3%* and 14.8%* against NSGA-II, respectively, and reductions of 12.6%# and 4.1%# against KGA, respectively. This implies that the convergence and computational efficiency in generating the pareto-solution by MTKGA is better than the two existing methods, while reductions in the use of SNs and RNs compared to the baseline setting are observed. Although the number of deployed SNs and RNs in MTKGA is on average higher than the other two strategies, it exhibits significant improvements over the baseline (by 52.66%). Apart from the deployment cost, the MTKGA also focuses on improving the execution time and average crowding distance. According to Hamdy et al. (2016), the MTKGA has better performance of GDn and n_{pos} in the multi-objective optimization process. This implies that the deployment cost can be reduced by using a smaller number of SNs and RNs when compared to the baseline, and the optimization process of MTKGA is more efficient that the other two strategies. The pareto fronts among the objective functions can be formulated afterwards, such that specific compromised solutions can be obtained through setting the designated weights for the objectives.

Table 6.2 Comparative analysis between baseline, NSGA-II, KGA and MTKGA

Performance	N_{exe}	Baseline	NSGA-II	KGA	MTKEGA
20SNs + 5RNs (S1)					
GDn	100	-	0.1831*	0.1757$^{\#}$	0.1564$^{*\#}$
n_{pos}		-	18	20	22
n_{sn}		20	8.17	7.35	9.00
n_{rn}		5	2.11	1.94	2.27
t_{exe}		-	9.2556*	8.8222$^{\#}$	8.3373$^{*\#}$
50SNs + 10RNs (S2)					
GDn	100	-	0.1756*	0.1327$^{\#}$	0.1243$^{*\#}$
n_{pos}		-	22	25	39
n_{sn}		50	22.73	24.24	24.95
n_{rn}		10	4.64	4.48	4.72
t_{exe}		-	28.8817*	29.4433$^{\#}$	25.5512$^{*\#}$
100SNs + 20RNs (S3)					
GDn	100	-	0.1104*	0.1046$^{\#}$	0.1098$^{*\#}$
n_{pos}		-	48	50	48
n_{sn}		100	42.94	54.54	49.17
n_{rn}		20	6.90	8.80	9.48
t_{exe}		-	86.6207*	87.0686$^{\#}$	70.5584$^{*\#}$

6.2.2 Evaluation of Blockchain Effectiveness and Efficiency in BDMM

6.2.2.1 Justification of the Integrated Consensus Mechanism

In the blockchain mechanism, there are several protocols to achieve consensus between the devices or stakeholders on a distributed network, such as PoW and PoS (Kshetri, 2017). However, the above protocols are designed mainly for initial coin offering (ICO) as a kind of technological development by using cryptocurrency. Apart from implementing blockchain in the financial industry, the extension of blockchain in supply chain management is the focus of this study, so that PoSCS is developed to fulfil the roles of PoW and PoS in the supply chain. Table 6.3 displays a comparison between the four consensus mechanisms and PoSCS for the five major aspects.

Table 6.3 Comparison between PoW, PoS, PoI, PoA and PoSCS

Aspect	**PoW**	**PoS**	**PoI**	**PoA**	**PoSCS**
1. Consensus algorithm	Pooled mining	Deterministic selection	Probabilistic selection	Deterministic selection	Probabilistic selection
2. Role for block creation	Miner	Validator	Harvester	Selected validator	Validator
3. Factors for miner/validator selection	Computational power	Wealth	Vested coins, transaction partners, monthly number and size of transactions	Reputation	Transit time, stakeholder analysis, shipment volume
4. Incentives	Reward	Transaction fee	Transaction fee	No	No
5. Computational power	High	Low	Low	Low	Low

The typical consensus algorithms, i.e. PoW and PoS, are not appropriate for application in supply chains, because supply chain activities are difficult to measure in monetary value, and incentives for maintaining the miners are lacking. Further, PoW requires a high level of computational power to compete with other miners to mine the blocks, which is an inefficient way in most of the application areas. Moreover, most supply chain parties (who are not listed companies) are not willing to disclose their business assets and financial status. Hence, applying PoS in supply chains requires modifications and extensions of the consensus algorithm. Proof of importance (PoI) and proof of authority (PoA) are two emerging consensus mechanisms. PoI focuses on the importance of accounts to harvest a block, while PoA requires a strict selection process to choose an authorised validator to mine a block (Li et al., 2017; Sankar et al., 2017). While PoI and PoA are being developed for ICO applications, their mechanisms consider additional factors apart from wealth and capital value of the accounts. Such concepts can be further extended to develop an appropriate consensus mechanism for food traceability. Accordingly, PoSCS is developed to select validators in a probabilistic manner to forge and validate the blocks in the blockchain. Its consensus algorithm considers transit time, stakeholder analysis, and shipment volume in the supply chain, instead of computational power and wealth. Therefore, the consensus mechanism in the blockchain can be practically applied in PFSC for food traceability.

On the other hand, the use of a consensus algorithm in a distributed network is required to prevent holding 51% of network tokens by a single party. In PoW, for a single party to control ≥51% of network tokens is difficult, requiring an extensive level of computational power. In PoS, PoI, and PoA, it is much more difficult to achieve, as a single party needs to have ≥51% of the total wealth in the network. To propose the new consensus algorithm, such as PoSCS in PFSC, the above consideration should be evaluated to maintain network sustainability. Accordingly, 30 stakeholders in the supply chain network are selected to conduct a comparative analysis between the following various combinations of PoSCS formulations: (i) transit time (C1), (ii) integration of transit time and stakeholder analysis (C2), and (iii) integration of transit time, stakeholder analysis and shipment volume (C3), as shown in Figure 6.1. Merely considering transit time in the supply chain network is not reliable for inferring the value or stake of the stakeholders. Therefore, the stakeholder analysis and shipment volume are integrated with the transit time to establish the weight measurement in PoSCS. It is found that C2 and C3 outperform C1 in reflecting the business performance and power among their peers, and the difficulties for stakeholders of reaching 51% of total network stake is increased, as stakeholders have to obtain these high proportions in the three factors of the consensus algorithm simultaneously. Further, C2 is a deterministic way of measuring the weights, which does not consider the up-to-date business performance and level of active participation in the industry. Therefore, the formulation of C3 for supply chain stakeholders in using blockchain applications is more comprehensive. In addition, stakeholders who are able to obtain higher value from food traceability and have a high level of active participation in supply chain activities will have a higher standardised weight in PoSCS.

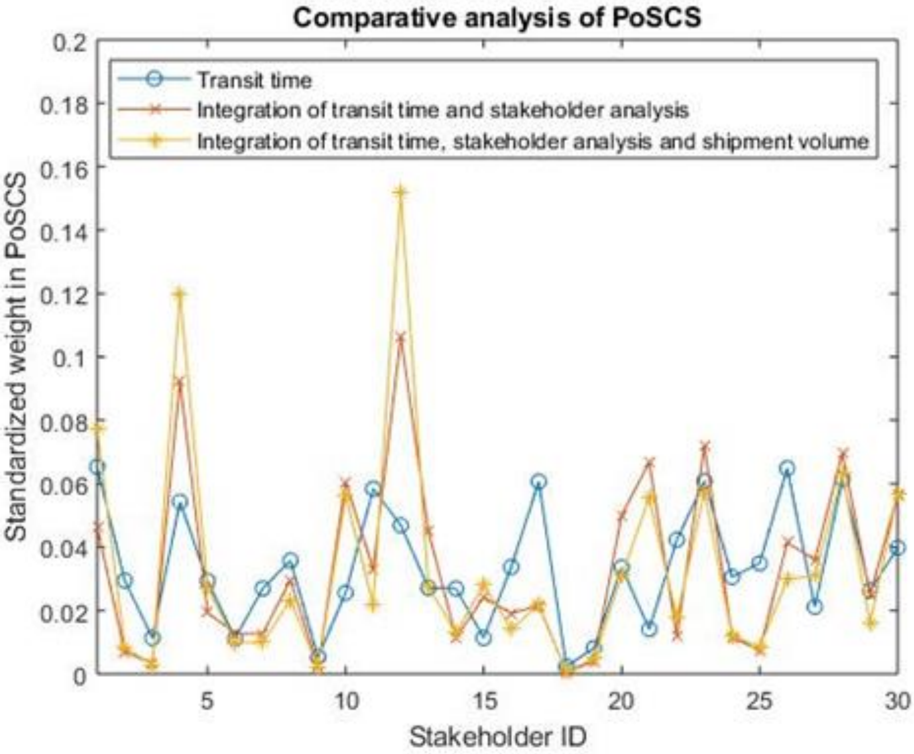


Figure 6.1 Evaluation of the performance of PoSCS

6.2.2.2 Time Efficiency in Block Forging

The proposed blockchain–IoT mechanism includes lightweight and vaporised characteristics in the blockchain, which has a positive effect on efficiency in the forging process. Regardless of the consensus algorithms, validators in blockchain need to calculate the hash values that fulfil the restrictions in the hash algorithm, by adjusting the random number in the block. Typically, each milestone of food traceability needs to collect information on the shipper, consignee, environmental conditions, battery level, and shipment status, namely {"id":{"sid":"","cid":""}, "cond":{"temp":"", "humi":"", "batLv":""}, "status":""} in JSON format. In the proposed system, all the above activity tracking information is managed in a centralised cloud database, and the associated identifies, namely {"assoId":""}, are stored in the blockchain. The efficiency of the proposed lightweight block forging mechanism is examined by the differences in computational time and iterations through conducting experiments on 50 sets of traceability data and associated IDs, under three levels of difficulty restrictions, i.e. target hash value beginning with “0”, “00” and “000”. The difficulty for generating hash values in forging blockchain is used to maintain the security and system synchronisation in the supply chain network. All the results were obtained using MATLAB 2019a, and conducted in the Windows 10 environment with an Intel Core i7-6770HQ @ 2.60 GHz and 32 GB RAM. In the block forging process, the value of forging difficulty, process delay time, and number of iterations are set for aiding and monitoring the loop progress. The execution time and number of iterations are collected to evaluate the block forging efficiency between using the entire traceability data and the associated IDs. Table 6.4 shows the results of the average execution times and number of iterations from the comparative analysis under various levels of block forging difficulty. It was found that using associated IDs to replace the whole traceability data resulted in lower execution times and number of iterations (on average) for obtaining the target hash value. Thus, the computational resources for block forging can be reduced by using the associated IDs. As shown in Figures 6.2-6.4, the performances of the block forging under various levels of difficulties were obtained. Along with increasing the difficulty of the block forging process, the time and iterations spent in the process by using associated data became less than when using the whole traceability data. Therefore, the synchronisation in peer-to-peer networks can be controlled more precisely by using associated data. The validated blocks need to be propagated globally to all nodes through the synchronisation stage, so that the time of synchronisation should be set properly to prevent information mismatch or lag in the whole distributed network. By carrying less information in the blocks, the time for forging blocks can be reduced, meaning the control of synchronisation can be enhanced.

On the other hand, the size of the blockchain (in bytes) can be decreased by reducing the number of characters stored in the blocks. In the distributed supply chain network, the number of blockchains is based on multiplying the number of SKU and the amount of food quantity (Q), i.e. $\mathrm{N_{blockchain}} = \mathrm{SKU} \times \mathrm{Q}$. The lightweight and vaporised features in the blockchain are significant for controlling the storage spaces for blockchain applications, rather than enlarging the size of blockchain applications without limits. Therefore, the proposed blockchain–IoT food traceability model has been developed to cater for the requirements of real-life industrial situations in food traceability.

Table 6.4 Average Execution times and iterations of block forging process

	Target hash value beginning with					
	"0"		"00"		"000"	
	Time (second)	Iteration (times)	Time (second)	Iteration (times)	Time (second)	Iteration (times)
Using whole traceability data	0.14	205.96	47.50	$7.18\text{x}10^4$	9626.25	$1.62\text{x}10^7$
Using associated IDs	0.16	254.60	38.94	$6.15\text{x}10^4$	5138.13	$8.43\text{x}10^6$

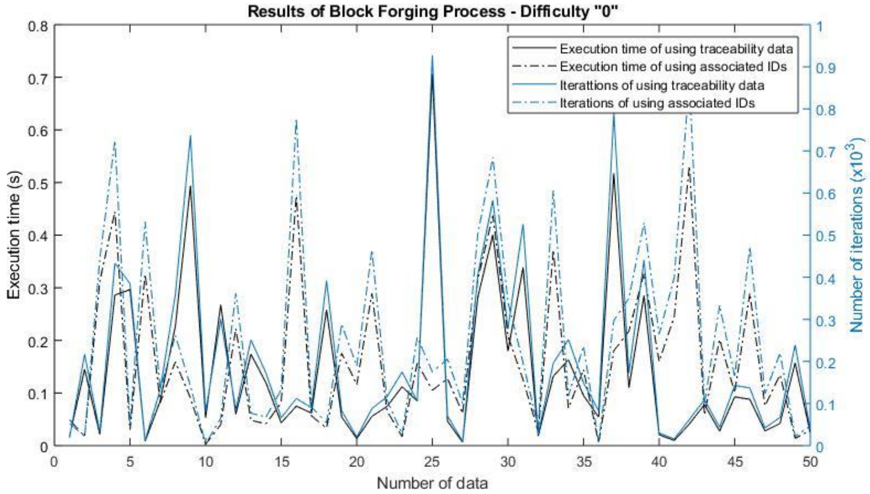


Figure 6.2 Block forging performance with target difficulty "0"

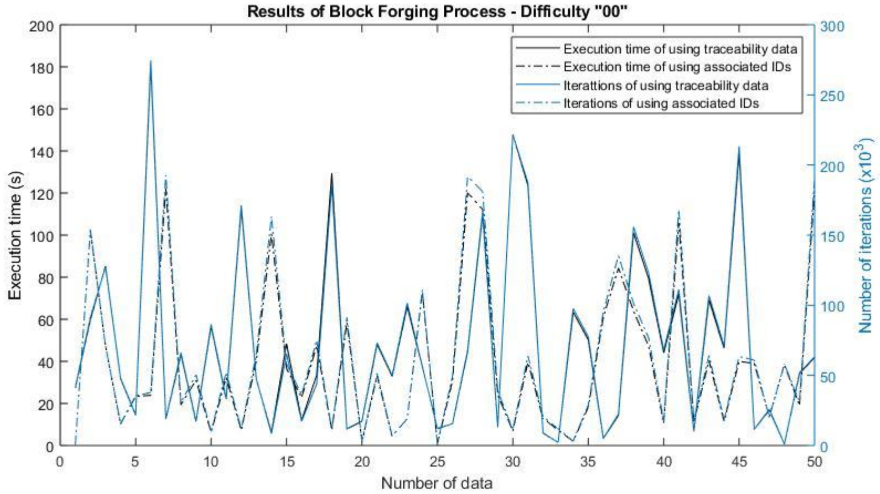


Figure 6.3 Block forging performance with target difficulty "00"

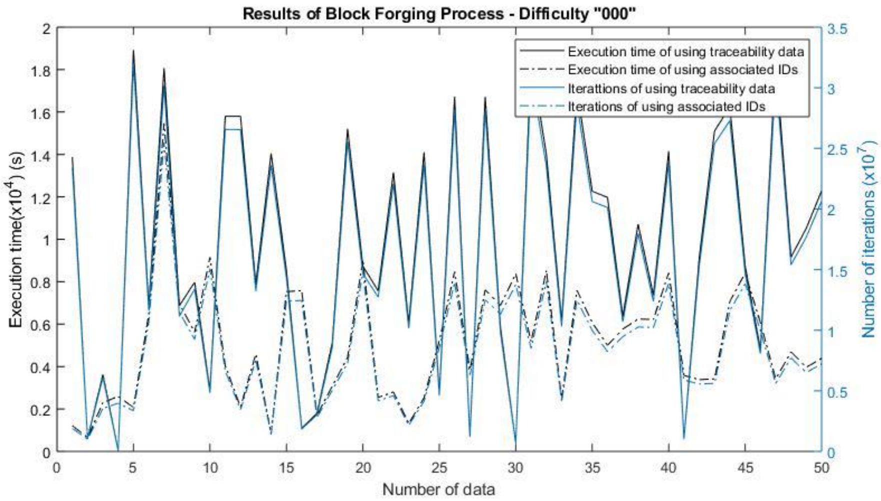


Figure 6.4 Block forging performance with target difficulty “000”

6.3 Discussion of the Case Studies

Apart from examining the general performance of the BIOMES, the effectiveness of the proposed system observed in the two case studies is also evaluated and discussed in this section. To measure the practicality of the proposed system, investment analysis and KPI measurements are included.

6.3.1 Investment Analysis of the Proposed System

The case studies, for the first time, formulated the customized design of cold chain packaging to the perishable food. Since logistics companies use refrigerated trucks for distributing the multi-temperature food, a certain level of food loss and capital loss can be estimated. The LSPs will have less motivation if the system investment in the proposed system cannot cover the loss and create more business opportunities. As mentioned above, the original percentage of the average food loss is about one-fifth of the total transactions. For handling premium imported food, the capital loss caused by the food spoilage and contamination is considered to be huge such that the motivation for implementing the FQMM in the BIOMES should be increased. For investigating the motivation, a cost analysis was carried out to examine the cost-effectiveness of the proposed system. At the beginning, the implementation cost of BIOMES included the set-up and equipment costs, which refers to the purchasing of sensor nodes and relay nodes, as well as system installation. Since two case studies were conducted, some variable costs were incurred, including the number of used sensors and relay nodes, types of eutectic plates, and the requirements of the IoT development platform. Therefore, the implementation cost regarding the system set-up, IoT equipment and services were estimated approximately. The performance of the system implementation was then measured by the average capital loss for food spoilage, average penalty, and annual compensation to customers. Table 6.5 shows the costs associated with the system deployment, and the cost performance indicators before and after the implementation. Based on the above information, the total cost saved per year is:

HK${[(*average capital loss for food spoilage per month before implementation* – *average capital loss for food spoilage per month after implementation*) + (a*verage penalty per month before implementation* – *average penalty per month after implementation)*] × 12 + (*annual compensation spent to customers before implementation* – *annual compensation spent to customers after implementation*) – *annual system maintenance cost* }

According to Table 6.5, the highest amount of cost-saving:

= HK${[(75,000 – 35,000) + (13,000 – 5,000)] × 12 + (70,000 – 28,000) – 30,000}

= HK$588,000

According to Table 6.5, the lowest amount of cost-saving:

= HK${[(68,000 – 45,000) + (10,000 – 7,000)] × 12 + (63,000 – 30,000) – 40,000}

= HK$305,000

Therefore, the expected break-even point can be calculated as follows:

System investment ÷ total cost saved

$$= \left[\frac{550{,}000}{588{,}000}, \frac{650{,}000}{305{,}000}\right] = [0.94, 2.13] \text{ years}$$

From the above analysis, the company is expected to invest between HK$580,000 and HK$650,000 at the beginning for system development and installation. Since the performance of BIOMES in maintaining the food quality and information visibility during the MTEF process has been verified, a continuous improvement in cost saving related to food spoilage and transportation penalties can also be expected. In addition, the company only requires 0.94 to 2.13 years to get back the money invested. This break-even duration is acceptable for the case company, striking a balance between the costs and benefits in maintaining the prescribed food quality, food traceability and information visibility to supply chain stakeholders.

Table 6.5 Cost analysis of the part of FQMM in BIOMES

	Implementation cost (in HK$'000)	Before implementation (in HK$'000)	After implementation (in HK$'000)
System set-up cost	100 - 140	/	/
IoT equipment and services	350 - 400	/	/
Blockchain services	100 - 110	/	/
Annual system maintenance cost	/	/	30 - 40
Average capital loss for food spoilage per month	/	68 - 75	35 - 45
Average penalty per month[a]	/	10 - 13	5 - 7
Annual compensation spent to customers	/	63 – 70	28 - 30

[a] Penalty incurred by late delivery and waste of transportation costs

6.3.2 Overall Performance of the Proposed System

With the aid of BIOMES in the case studies, the MTEF process has been improved by streamlining the information flow through the blockchain-enabled IoT system, and the food quality management through the use of customized passive packaging and shelf life evaluation for specific food items. Subsequently, the multi-temperature last mile delivery can be established to consider the multi-temperature specifications in the vehicle routing problem. It is found that the food spoilage rate during transportation is reduced, and customer satisfaction and operational efficiency are enhanced. To examine the effect after using the BIOMES, a sample survey was conducted for both end customers and internal staff members to assess the customer-related, operation-related and information-related perspectives. The survey was conducted with a 3-month timeframe between the selected perishable food and other perishable food in the e-commerce platform. Table 6.6 shows the results of the performance analysis of the new system in this study, and the findings indicate the positive effectiveness in the practical PFEC environment.

First of all, end customers in the e-commerce platform have positive feedback related to the shopping experience and logistics services, where the customer feedback was quantitatively measured by the average number of the monthly customer complaints, customer satisfaction and customer confidence in the PFEC business. After implementing the BIOMES, the monthly customer complaints was on average, changed from 12 to 5, a decrease of 58.3%. The customer satisfaction and confidence were increased from 5.8 to 6.9 (+19.0%) and from 5.2 to 7.6 (+46.2%), respectively. The above findings show the positive impact obtained from the implementation of

BIOMES, which is beneficial from the viewpoint of the end customers.

Table 6.6 Performance analysis of the proposed BIOMES

Area	**Before using BIOMES**	**After using BIOMES**	**Percentage change**
Customer related:			
-Monthly customer complaint	12	5	-58.3%
-Customer satisfaction	5.8	6.9	+19.0%
-Customer confidence	5.2	7.6	+46.2%
Operation related:			
-On-time performance on fulfillment orders	66.2%	78.4%	+18.4%
-Average time for picking and packing operations	8 min	10 min	+25.0%
-Average monthly number of return deliveries	15.3	7.4	-51.6%
Information related:			
-Environmental monitoring	Manual	Real-time	N/A
-Time for food traceability per order	3 days	~10 seconds	N/A

Secondly, with the use of BIOMES, the packing and delivery processes are improved by using cold chain packaging customization and multi-temperature delivery. The findings show that there were positive impacts in the aspects of on-time order fulfilment and reduction of return deliveries, by 18.4% and -51.6%. The proposed system can strengthen the delivery performance when handling multi-temperature products under the e-commerce environment, while the return shipments due to food deterioration and spoilage are greatly reduced. However, there is a negative impact generated by the proposed system, in prolonging the time for order picking and packing operations. Since the front-line staff members need to follow the instructions from the BIOMES for the outer cold chain packaging, the time for such operations was increased but the quality of perishable food was further secured during the logistics process. Lastly, as the proposed blockchain-enabled IoT system was implemented in the case company, the functionalities of the environmental monitoring and food traceability were further improved to provide real-time monitoring and reliable data management. Regarding the process of food traceability, the time used in tracing the historical activities and records were dramatically reduced from 3 days to approximately 10 seconds, achieving efficient and effective food traceability in the e-commerce industry. Since the above assessment of the system performance relied on the limited number of foods in fresh fruit and meat products, additional number of food items and types can be considered in the future assessment so as to verify the proposed system in a systematic manner.

Apart from conducting the survey to industrial practitioners, the implementation of the proposed provided the high degree of scalability in the MTEF environment, while the trust between supply chain stakeholders could be established effectively through the use of blockchain technology. Scalability, which refers its capability to handle tasks and events when the system grows in size, should be measured in terms of data size, frequency, and types in the BIOMES. The lightweight characteristics generated a high degree of flexibility to manage additional data for the food traceability, in which the entire data payloads were stored in the cloud to formulate a software as a service (SaaS). On the other hand, consensus among supply chain stakeholders was built effectively in the decentralized network. In the network, the collaboration of all stakeholders to sustain the blockchain-enabled IoT system was needed, in which the blockchain provided the natures of decentralization, immutability, traceability and transparency. Consequently, the trust among supply chain stakeholders was developed in this study as the data from the proposed system cannot be modified and are independently verifiable.

Compared with the traditional IoT approaches (non-blockchain-enabled IoT system), the data management in the proposed system for traceability and transparency has been greatly strengthened so as to benefit the establishment of effective food traceability for the PFEC businesses. In addition, the system reliability has been improved to prevent data tampering and cyber-attacks to the management systems for operating PFEC. Having the proposed system in the MTEF process, the trust developed in the supply chain network was the most valuable which can promote and encourage the development of the PFEC businesses to deliver the food items to end customers with high quality and safety standards.

6.4 Implications for MTEF Process in PFEC

In recent decades, the development of general e-commerce businesses that cater for most general commodities and daily consumables are mature and well-established in terms of e-commerce platform management, e-order fulfilment, and home delivery for fragmented orders. To evolve e-commerce businesses further, PFEC (which is the focus of this study) is one of the means of extending existing services and products provided to end customers. However, selling perishable foods, or even perishable items which are environmentally-sensitive, requires additional functions for order fulfilment processes for which existing practices do not yet cover. In the past, end customers who wanted to purchase perishable foods could touch, see, and smell the physical products to evaluate food quality; however, this cannot be achieved in e-commerce platforms. Consequently, customers can only rely on the descriptions provided by vendors, and feedback from other customers regarding historical transactions. Accordingly, customers cannot directly evaluate and monitor the quality of perishable foods to be purchased. Thus, confidence from end customers to e-commerce platforms for purchasing perishable foods is relatively weak. On the other hand, in traditional e-commerce businesses, quality discrepancy between products is mainly contributed to by the corresponding vendors. Vendors have the sole responsibility of sourcing and producing high-quality products for selling on e-commerce platforms. However, when handling perishable foods, LSPs also have the responsibilities of ensuring and maintaining food quality in e-fulfilment centres and last mile delivery in addition to the vendors. Therefore, this constitutes an additional risk factor and a responsibility to be considered in PFEC businesses, and LSPs need to mitigate these risks by enhancing the existing e-fulfilment process. Consequently, enhancements in e-fulfilment processes (MTEF processes) in aspects of resilient data acquisition, food traceability, and food quality management are significantly important to the development and sustainability of PFEC businesses.

The practical significance of using BIOMES in the MTEF process consists of three aspects. First, IoT data acquisition (i.e., the IoTDM) provides real-time environmental monitoring and an IoT deployment framework to create total monitoring of perishable foods along the supply chain. Second, blockchain-enabled data management (i.e., BDMM) supports the establishment of reliable and secure food traceability from farm to end customers under the environment of PFEC. Third, food quality management (i.e., FQMM) consists of customised packaging and quality evaluation for specific batches of food according to the handling specifications and collected data. Further, last mile delivery can be strengthened by considering multi-temperature characteristics. Overall, the above measures can improve the order fulfilment process for handling perishable foods, while customer confidence in PFEC businesses can also be built to facilitate online trade for perishable food.

6.5 Summary

This chapter provides detail evaluation and discussion of the research results. On the one hand, the system performance the BIOMES was investigated in the aspects of (i) optimization process about MTKGA and (ii) justification of the blockchain integrated in IoT system. The proposed MTKGA was compared with other existing optimization methods and the baseline measurement from WHO TRS 961. Also, the value and efficiency of the proposed PoSCS stood out in comparison with the existing consensus mechanisms and measuring its time efficiency in the block forging process. From the perspective of the case studies, the system investment and overall performance were discussed to show the practicality and cost-performance balance, which are summarized from the case studies in Section 5. Overall, it was found that the development and implementation of the proposed system proved significantly important to the MTEF process under the PFEC business environment by effectively enhancing its environmental monitoring, food traceability and food quality management.

Chapter 7 Conclusions

7.1 Summary of the Research

Due to the rapid growth of e-commerce businesses all around the world, practitioners need to continue enriching product categories and services to maintain a large group of customers. Accordingly, perishable food products have been added to numerous e-commerce platforms recently. However, current e-fulfilment processes do not fully cater for the needs of handling perishable foods, resulting in dissatisfaction of end customers and poor efficiency of the e-fulfilment process. In traditional e-commerce businesses, trust between end customers, vendors, and platforms can be built effectively through systematic data management, grading of vendor trustworthiness, and customer comments. Further, deviation of product quality is mainly considered the responsibility of the vendor. However, under the environment of PFEC, this cannot be achieved using the same e-fulfilment processes, because perishable foods have a shelf life and environmentally-sensitive characteristics. Therefore, the ontology of the MTEF process is considered in this research to explore how to enhance e-fulfilment processes when handling multi-temperature food products, which have their own environmental excursion specifications for storage and transportation.

Motivated by the aforementioned issues, the aim of this research was to design and develop an intelligent system (BIOMES) by integrating IoT technology, blockchain, and applied artificial intelligence to enhance the areas of environmental monitoring, food traceability, and food quality management in the MTEF process. The proposed system integrates IoT and blockchain technologies for real-time data collection and reliable data management to strike a balance between real-time environmental monitoring and the formulation of food traceability. Subsequently, food quality in the PFEC environment is further enhanced by the use of cold chain packaging design, and food quality customisation in terms of shelf life and quality decay assessment. Furthermore, delivery route planning is improved by considering multi-temperature food characteristics to ensure appropriate environmental conditions during transportation.

Overall, the four aforementioned research objectives have been successfully accomplished. For objective one, a three-stage optimisation model of ESN was achieved for fulfilling the requirements of environmental monitoring and mapping. For objective two, a blockchain-driven IoT system was designed and developed for food traceability in the PFEC industry. For objective three, food shelf life and quality decay were measured in the e-fulfilment centre to improve supply chain visibility. For objective four, a passive cold chain packaging model was proposed to ensure effective environmental excursion management in last mile delivery, and to obtain the factor of maximum time allowed for transportation for the establishment of multi-temperature delivery route planning.

This research has contributed at both application and theoretical levels. At the application level, the proposed system enables LSPs to strengthen their existing e-fulfilment processes to cater for the fast-growing trend of PFEC. Transparency, traceability, and food quality management can be established to improve operational effectiveness and efficiency, while customer satisfaction and confidence in PFEC can be enhanced. Overall, the positive atmosphere of PFEC businesses can be fostered, resulting in better establishment of the eco-system of PFEC. At the theoretical level, an IoT deployment scheme was optimised by using the newly proposed MTKGA to obtain better solution convergence and efficiency. In addition, an integrated consensus mechanism was developed to achieve food traceability among various supply chain stakeholders to provide a practical and flexible blockchain application. In addition to blockchain development, lightweight and 'vaporized' characteristics were embedded to improve adaptability and scalability further. Therefore, a blockchain-enabled IoT system was developed in entirety to perform real-time data acquisition and reliable data management effectively, and to support food quality management measures in the PFEC environment.

7.2 Contributions of the Research

In this research, a generic methodology is proposed for designing and developing an intelligent system to strengthen the MTEF process in the PFEC business environment. The proposed work improves three major areas of the MTEF process: environmental monitoring, food traceability, and food quality management. Accordingly, the contributions of this research are summarised as follows:

(i) The BIOMES is designed and developed as a new architecture for PFEC businesses to strengthen functionalities in the MTEF process. The proposed system is an integral solution to eliminate the challenges faced by PFEC businesses. Through the hybridisation of IoT technologies, blockchain, and applied artificial intelligence, an effective e-fulfilment process in terms of environmental monitoring, food traceability, and food quality management can be established. The research results are beneficial to both end customers and LSPs, enabling them to have better customer confidence and operational effectiveness, respectively.

(ii) By deploying IoT technologies in this research, a customised three-stage IoT deployment scheme is designed that considers two new factors (environmental fluctuation and fuzzy-based system lifetime) and four essential factors (cost, coverage, connectivity, and fault tolerance). Further, the proposed scheme integrated the features of environmental monitoring and mapping analysis to form closed-loop control of IoT deployment. Moreover, optimisation of the above deployment problem is achieved by using the proposed MTKGA in which the multi-response Taguchi method and K-means clustering are embedded in the NSGA-II to improve solution convergence and optimisation efficiency.

(iii) Regarding the establishment of food traceability, blockchain technology is used, in which the integrated consensus mechanism (PoSCS) and hybridisation between IoT and blockchain are described. Formulation of PoSCS considers the average transit time in their roles, stakeholder assessments, and monthly shipments to assign corresponding weights to all involved supply chain stakeholders. This can facilitate the process of block forging, and provide a commonly acceptable method to maintain the distributed network. Moreover, when handling real-time data from IoT technologies, lightweight and transparent characteristics are also established in the blockchain to improve system practicality and adaptability.

(iv) In the PFEC environment, food quality is always a critical element that enables end customers to trust food products sold on the platforms. To enhance food quality management, this research provides cold chain passive packaging to address fragmented e-orders and multi-temperature delivery route planning to meet handling requirements. In addition to the above, shelf life adjustment and quality decay evaluation are performed in a customised manner for every batch of perishable food, and the information is disclosed to end customers to improve transparency before and after purchasing.

(v) The proposed system (BIOMES) has also been successfully implemented in an LSP dedicated to exploring PFEC businesses. By conducting two case studies in fresh fruit and meat products, the practical values of the proposed system can be validated for strengthening functionalities of the MTEF process, and the BIOMES is shown to be feasible in the PFEC environment.

7.3 Limitations of the Research

Although this research makes several contributions in both application and theoretical aspects, three limitations are observed and summarised as follows:

(i) The selection of IoT devices and sensors is in accordance with the requirements of environmental control and monitoring throughout the perishable food supply chain to establish environmental excursion management, which mainly concerns temperature and relative humidity. However, regarding the handling of perishable foods, IoT sensors such as electronics noses, which enable the functions of analysing chemical vapour (such as carbon dioxide and oxygen), are not considered during the investigation of e-fulfilment centres.

(ii) The reasons for applying IoT and blockchain technologies in this research are as follows: (i) manage collected data related to environmental monitoring and food traceability, and (ii) identify food products along the food supply chain. However, verification of the claimed identification of food items along the entire supply chain is limited in this study such that the food authentication by means of IoT and blockchain technologies is achieved by means of identification only. On the other hand, mutual trust and high security standards among supply chain stakeholders can be further improved. Moreover, to achieve consensus in the distributed blockchain network, the stakeholder with the highest bargaining power is located to spread the use of blockchain applications to other stakeholders.

(iii) Regarding cold chain passive packaging, the factors concerned in the experimental design are limited to specific eutectic gels and certain sizes of polyfoam boxes. Further, the Taguchi method used in the design of cold chain passive packaging can only evaluate a single objective (i.e., maximum time allowed for transportation) in this research; therefore, the objectives of cold chain packaging design can be further enriched to improve its practicality.

7.4 Suggestions for Future Work

To address the limitations of this research and conduct further research in the field of PFEC, there are three future directions regarding the proposed system to improve functionalities of the MTEF process. These are summarised as follows:

(i) Additional IoT sensors and devices (including e-noses and sensory analysis) can be considered and connected to the same IoT development platform via standard IoT protocols (e.g., MQTT) to perform other quality-oriented functionalities. In addition, with higher capability in IoT technologies, the application areas of the proposed system can be extended to other environmentally-sensitive and high-value products, such as pharmaceuticals and luxury products. In addition, the calibration scheme of the sensor network should be considered to ensure the reliability and consistency of the electronic readings which are contributed to the optimization of ESN deployment.

(ii) With the sophisticated blockchain-enabled IoT system, food authentication can be further introduced in the PFEC environment to improve accuracy of the data to be forged in the blockchain. The object-specific features, tag authentication, and location-based authentication can be considered in the blockchain–IoT system to eliminate vulnerability of the traceability and blockchain applications. Also, in-depth statistical analysis to verify the benefits obtained in the industry can be studied with considering additional food items and types, and the trust and perception from end customers can be evaluated and modelled.

(iii) With regard to cold chain packaging, additional factors and objectives can be considered in the experimental design model. The multi-response Taguchi method can be further applied in the formulation of cold chain packaging by considering the preparation time of the packaging and additional packaging materials. Moreover, the sustainability of applying cold chain packaging can also be considered so that the research impact on resource management can be strengthened.

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