An Internet of Things (IoT)-based Shelf Life Management System in Perishable Food e-Commerce Businesses

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Abstract—**In recent years, the rapid development of e-commerce businesses has led to an evolution in the perishable food supply chain, such that perishable food e-commerce businesses have been established for covering business-to-business (B2B) and business-to-customer (B2C) transactions. For handling perishable food, accurate shelf life management plays an essential role in estimating product shelf life and in formulating quality degradation model. However, existing methods in shelf life estimation may not be applicable under the e-commerce environment in considering the wide variety of products, fragmented customer orders, and short delivery timeframe. On the other hand, environmental monitoring is another key element for determining ambient environmental conditions, such as temperature and relative humidity, which are used to formulate the quality degradation model. With the emergence of Internet of Things (IoT) technologies, dramatic enhancements in environmental monitoring with improved power efficiency, security and transmission effectiveness are available. In this paper, an Internet of Things based Shelf Life Management System (ISLMS) is proposed which integrates IoT technologies, fuzzy logic and zero-order quality degradation modelling for handling perishable food. Data acquisition throughout the entire e-commerce business can be done automatically in a cost-effective manner. The collected data is then used to adjust the product shelf life and specific rate of quality degradation, with the rate being applied to the quality degradation model. The environmental changes are taken into consideration during the entire supply chain journey, such that the perishable food is handled by all-round shelf life management. As a consequence, with the adoption of ISLMS, perishable food can be safely managed under the e-commerce environment, while information visibility and customer confidence are further enhanced.**

I. Introduction

Perishable food supply chain management (PFSCM) which is a specific area in the cold chain industry always attracts lots of attention from both industry and customers in maintaining designated food quality throughout the entire supply chain. To achieve the preferred goals, particular refrigeration systems are used to create suitable environmental conditions for handling perishable food, while monitoring and traceability systems, such as ezTRACK, have been developed to identify and ensure the products are handled within the required handling specifications. Recently, there has been a dramatical change in PFSCM in the aspects of payment methods, customer behavior and logistics management, due to the blooming of the e-commerce businesses [1-2]. Differing from the traditional freight forwarding practice, e-commerce businesses can operate in four different modes, namely business-to-customer (B2C), business-to-business (B2B), business-to-business-to-customer (B2B2C), and customer-to-customer (C2C). Thus, the efficiency of supply chain activities, information exchange effectiveness, and data accuracy are becoming more important than in the past, and the ontology of perishable food e-commerce (PFEC) has been established. Over the entire process in PFEC, customers are mainly concerned with the level of the received food quality, and it is one of the main factors that influence a company's image and future sales performance [3]. In other words, delivering perishable food with poor quality and service causes the increase in the rate of shipment return and damages the entire eco-system of the e-commerce business. To improve the above situation and maintain competitiveness, shelf life management, covering shelf life determination and quality degradation modeling, is of utmost importance in PFEC. However, the current methods in shelf life management have two major challenges, as shown in Fig. 1.

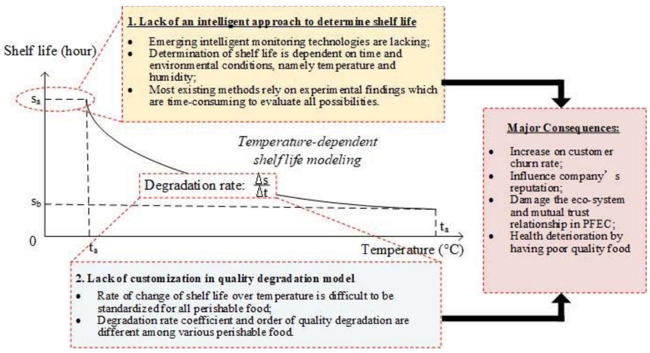

Fig. 1. Existing problems in perishable food e-commerce

In general, empirical studies and data analysis are conducted to calculate the original and remaining shelf life for specific products at the food processing centers. However, there is lack of an integrated system to collect environmental data over the whole supply chain for evaluating and adjusting the shelf life. On the other hand, the modeling of shelf life is environment-dependent, covering ambient temperature and relative humidity, and is also time-dependent. Hence, at first, an intelligent approach to determine the shelf life during supply chain activities is lacking, and it is time-consuming to conduct all-

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round experiments for the product so as to formulate its customized shelf life model. Secondly, the quality degradation model is another important element to assess the level of food quality throughout the supply chain. However, perishable food has its own specific characteristics in regards to the food deterioration rate, and thus a customized set of degradation rate coefficients and orders of quality degradation is difficult to be standardized. As a consequence, with improper shelf life management in PFEC, the customer churn rate, company reputation, and the e-commerce eco-system can be impacted. Worse still, it may cause the health problems if end customers consume the poor-quality food. In order to overcome the above challenges, an Internet of Things based shelf life management system (ISLMS) is proposed in this study to aid the process of shelf life determination and quality degradation modeling. With the adoption of IoT technology, the environmental monitoring for perishable food can be done automatically, and the collected data can be stored for shelf life management. To evaluate the shelf life and quality degradation, the fuzzy logic approach is adopted to handle the collected data so as to formulate customized adjustment and degradation model on the shelf life.

The remainder of this paper is organized as follows. Section II reviews the past literature concerning the overview of perishable food e-commerce, IoT technology, and artificial intelligence in shelf life management. Section III describes the architecture of the proposed ISLMS. Section IV presents a case study to validate the feasibility of the proposed system. Section V discusses the results and advantages of adopting the ISLMS. Section VI gives the conclusions.

II. Literature Review

In this section, an overview of perishable food e-commerce is firstly reviewed. The IoT technology and relevant artificial intelligence in the area of shelf life management are then discussed.

A. *Overview of perishable food e-commerce*

In recent years, great attention on PFEC has been paid due to increasing distribution demands and return demand, and the traditional methods in food supply chain management are inadequate to maintain effectiveness and efficiency [4]. The major differences between the traditional food supply chain and PFEC are that (i) the logistics modes have been changed from freight forwarding to a mixed mode of freight forwarding and e-commerce logistics, and (ii) parcel shipments with multi-temperature characteristics increase the complexity of the supply chain. Since customers are able to order different perishable food from the e-commerce platform, the consolidation of parcel shipments, in which each parcel may contain different perishable food, with its own specific handling requirements, creates an issue of multi-temperature transportation. Multi-temperature joint distribution was then proposed to address concerns on handling multi-temperature parcel shipments [5], resulting in formulating the distribution framework and cold chain packaging in order to consider and maintain a high level of food quality throughout the supply chain [6-7]. In view of the visibility and traceability, shelf life management is one of the core components to measure the shelf life and improve confidence in the products by customers. Food shelf life measurement is an active research area in the aspect of shelf life determination and quality degradation. The former is to estimate the food shelf life based on chemometric indicators, such as level of oxidation [8]. Such a shelf life determination process consists of three steps, namely preliminary study for critical events, simulation testing, and model formulation. The latter is to measure the decay rate of the food quality, and the Arrhenius equation is deemed to be the feasible for measuring the quality degradation. The apparent reaction order varies with different types of products, for example zero-order reaction for potato chips and first-order reaction for frozen vegetables. However, there is limited research for formulating an intelligent approach to assist experimental and empirical methods in shelf life measurement. In order to formulate such a shelf life measurement, the environmental data, for example temperature, humidity, light intensity and pressure, should be collected and managed in an effective manner by means of IoT technology.

B. *IoT technology in shelf life management*

Internet of Things (IoT) is an emerging concept for connecting objects, or called things, by using sensors, actuators, and other identification and sensing technologies so as to achieve the goals in creating values for the existing business process and operations. The IoT sensing system combines the features of wireless communication, intelligent sensor and radio frequency identification (RFID) technology, and the functions of sensing, actuation, identification, interaction and communication can be achieved. Therefore, it is deemed to be feasible in establishing a visibility and traceability system in handling perishable food, or even PFEC. To build a IoT system, there are generally four components, namely sensing layer, network layer, service layer and interface layer [9]. The specific business logic can be built inside the IoT system to interact with users in the general front-end applications. In the context of shelf life management, Qi et al. [10] proposed a decision support system based on wireless sensor networks to enhance shelf life visibility and match the strategy of least shelf-life first out (LSFO) in the cold chain industry. The time-temperature indicator feature was considered to let cold chain enterprises predict the shelf life and formulate a smart LSFO strategy. Cho et al. [11] presented an IoT solution to connect the point of sales (POS) system in food retail store with the home refrigerator. Once the food is bought by the customers, information, such as types of products, shelf life, and storage requirements, is then sent to the home refrigerator for better control of the perishable food. In this respect, IoT is an enabling technology, and an appropriate intelligent method for data analytics should be developed in the IoT system.

C. *Artificial intelligence in shelf life management*

To develop an intelligent system, artificial intelligence (AI) covers numerous techniques, for example fuzzy logic, genetic algorithms, neural networks and case-based reasoning for various industrial applications. Among several AI techniques, fuzzy logic is a technique to handle the fuzzy information and rule based inference so as to construct decision support in real-life applications. The crisp sets and linguistic information can be processed by the fuzzy sets with defined membership functions in a decision science approach [12]. Fuzzy set theory was applied to assess the shelf life of fried potato wedges by ranking metal oxide gas sensors as electronic noses [13]. 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 [14]. Furthermore, fuzzy set theory and fuzzy logic have the capability of integrating with other techniques of 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 [15-16]. However, there are limited studies for integrating fuzzy logic approach and shelf life assessment model so as to evaluate the shelf life and quality degradation rate.

With the above studies, the importance of PFEC is proven, and current work is focusing on enhancing its effectiveness and efficiency. Among research studies, shelf life management is one of the core elements required in PFEC, but it should be further enhanced by means of IoT technology and artificial intelligence techniques. There is room for improvement, which is done in this paper in integrating IoT technology, fuzzy logic and methods in shelf life management to formulate a novel shelf life assessment and quality degradation model in PFEC.

III. Design of An IoT Shelf Life Managemnet System

In this section, an Internet of Things based shelf life management system (ISLMS) is described with three modules, namely (i) IoT data collection module (IDCM), (ii) fuzzy shelf life management module (FSLMM), and (iii) quality degradation module (QDM), as shown in Fig. 2. It aims at customizing the shelf life and quality degradation pattern for perishable food based on the quality of past logistics activities, resulting in better assurance of food quality and temperature excursion management.

A. IoT data collection module (IDCM)

In the supply chain of PFEC, three parties, i.e. suppliers, e-fulfillment center, and customers, are the core components involved in e-commerce transactions. When the products are placed in the e-shop, they should be physically shipped to the e-fulfillment center, which is refrigerated or chilled according to the handling requirements, to await for the order creation, picking and packing process. The perishable food should be under tight monitoring and control, starting from the point of supply. Therefore, IoT sensor technology should be applied to capture the environmental conditions and to identify the particular batch of perishable food. In this paper, SensorTag CC3200, which is a cost-effective means for developing environmental monitoring and transmitting the data via Wi-Fi network, is attached to a batch of perishable food to obtain the environmental data, such as ambient temperature (°C), Infra-red temperature (°C), relative humidity (%), light intensity (lux), and pressure (kPa). The operation data, including the operational flow and supply chain activities, are also collected. The collected data are then stored in the cloud database for the analytics process via certain IoT protocols and Platforms as a Service (PaaS)-based IoT development platform. Before reaching the e-fulfillment center, the perishable food is shipped between various supply chain parties, and therefore the mean kinetic ambient temperature and mean kinetic relative humidity are applied to summarize the overall effect of environmental fluctuations during handling of the perishable food, before reaching the e-fulfillment center [17-18].

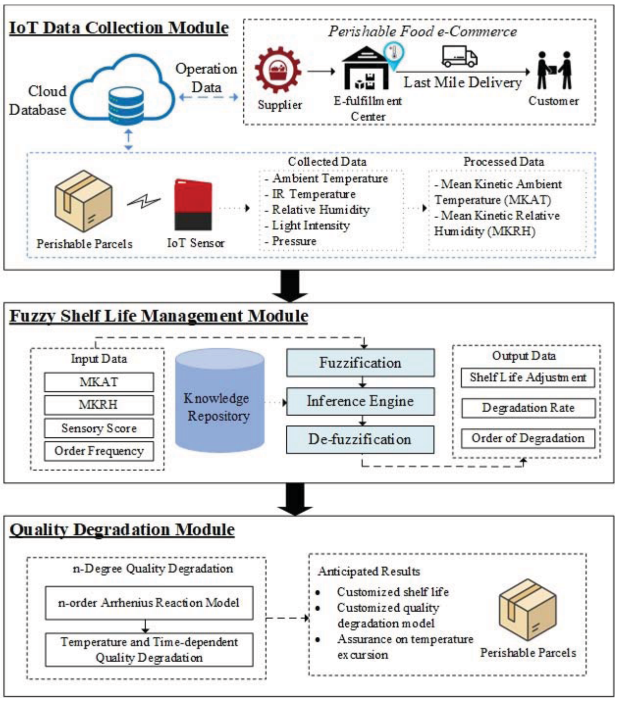

Fig. 2. System architecture of ISLMS

For the mean kinetic ambient temperature (MKAT), the effect of temperature fluctuation during the transit time intervals t = {t_1, t_2, …, t_n} with the corresponding ambient temperature AT = {AT_1, AT_2, …AT_n}and relative humidity RH = {RH_1, RH_2, …, RH_n}can be evaluated. Thus, the decay factor γ can be formulated as in (1), and the MKAT for the chosen designated relative humidity RH_d can be derived as in (2), where ΔH represents the heat of activation, B is the moisture-sensitivity term and R is the universal gas constant. Consequently, the overall temperature fluctuation for the time $\mathrm{t}_{\mathrm{total}} = \sum_{i=1}^{n} t_i$ can be summarized and measured in the supply chain.

$$\gamma = \ln\left(\frac{t_1 e^{\left(B(RH_1)-\frac{\Delta H}{R\cdot AT_1}\right)} + \cdots + t_n e^{\left(B(RH_n)-\frac{\Delta H}{R\cdot AT_n}\right)}}{t_1 + \cdots + t_n}\right) \quad (1)$$

$$\mathrm{MKAT} = \frac{\frac{\Delta H}{R}}{B(RH_d) - \gamma} \quad (2)$$

For the mean kinetic relative humidity (MKRH), similar to MKAT, the effect of fluctuation of relative humidity during the transit time interval t = {t_1, t_2, …, t_n} with the corresponding ambient temperature AT = {AT_1, AT_2, …AT_n}and relative humidity RH = {RH_1, RH_2, …, RH_n} can be evaluated. Therefore, the MKRH for the chosen designated ambient temperature AT_d can be derived as in (3), where ΔH represents the heat of activation, B is the moisture-sensitivity term and R is the universal gas constant. Eventually, the overall humidity fluctuation for the time $\mathrm{t}_{\mathrm{total}} = \sum_{i=1}^{n} t_i$ can be summarized and measured during the supply chain.

$$\mathrm{MKRH} = \frac{\frac{\Delta H}{R\cdot AT_d} + \gamma}{B} \quad (3)$$

B. Fuzzy shelf life management module (FSLMM)

In this module, the fuzzy logic approach is adopted to make use of environmental fluctuations, namely MKAT and MKRH and the operation characteristics of PFEC, namely sensory score and order frequency, to adjust the shelf life and assist in the formulation of the quality degradation model. The fuzz logic consists of four major components, i.e. fuzzification, inference engine, knowledge repository, and defuzzification. Before processing the fuzzy logic, the membership functions for the input and output data and IF-THEN rules for connecting input and output data are formulated and stored in the knowledge repository. Afterwards, the collected input data can be entered to the fuzzy logic. Firstly, fuzzification converts crisp values to fuzzy sets, for example "low", "medium" and "high" etc., expressing linguistic terms by using specific membership functions. In a mathematical expression, the input and output data D = {D_1, D_2, …, D_m} is integrated with the membership function μ_D to be fuzzy set F_i, as in (4).

$$\mathrm{F}_i = \sum\nolimits_{i=1}^{n} \frac{\mu_D(D_i)}{D_i} \quad (4)$$

In the inference engine, the Mamdani's inference method is used to aggregate the input fuzzy sets into the fuzzy output sets, expresses as fuzzy IF-THEN rules instead of a linear mathematical expression. The adaptability and ease of use are greatly improved for industrial applications. In addition, in the inference engine, the OR operator is applied for combining the output membership function values and formulating a bounded area in each output membership function. Lastly, in the defuzzification, the bounded area is then converted back to numerical values for the corresponding output variables Y_i, by means of the centroid method, as in (5). It is expected that the adjustment of shelf life, rate of quality degradation and order of quality degradation can be obtained for the specific batch/lot of perishable food at e-fulfillment center.

$$\mathrm{Y}_i' = \frac{\int_1^n Y_i \cdot \mu_{A_i}(Y_i)\, dY}{\int_1^n \mu_{A_i}(Y_i)\, dY} \quad (5)$$

C. Quality degradation module (QDM)

After customizing the shelf life, rate and order of quality degradation for the perishable food, the customized quality degradation model can then be established. Referring to the Arrhenius equation, the quality degradation model is established by building a relationship between food quality *q* and transit time *t* at the specific temperature with the certain rate of quality degradation *k* and order of quality degradation *n*, as in (6).

$$\frac{\Delta q}{\Delta t} = -kq^n \quad (6)$$

According to the customized settings obtained by FSLMM, the customized quality degradation model can be formulated for perishable food during the supply chain process. The remaining shelf life can be readily calculated. Therefore, the e-fulfillment center can monitor the transported perishable food, and the customers are able to track the real-time status and shelf life information regarding their ordered food. All in all, the supply chain visibility is improved, while the customer confidence in the food quality can be further enhanced. This will foster a good atmosphere in the eco-system of PFEC.

IV. Case Study

In order to validate the proposed approach in a real-life situation, a case company located in Hong Kong was selected for adopting the ISLMS to assist and improve their perishable food e-commerce business.

A. Company background

ABC Limited, originally, is a third-party logistics company in Hong Kong, originally providing freight forwarding, warehousing, transportation and any other value-added services. Taking advantages of its logistics premises and corresponding experience, it has expended its business to the e-commerce market by providing integrated e-fulfillment and last mile delivery for e-commerce orders. Apart from the logistics functionalities, ABC Limited also provides m-commerce and e-business services to their customers so as to vertically integrate the logistics services and e-commerce platforms. The e-commerce business covers general commodities, perishable food and beverage products. Their customers are required to keep stock in the e-fulfillment center first, and the items are ready for picking and packing when the e-commerce orders are received. Through the e-commerce and m-commerce platforms, customers can easily place orders for the items which they want, and complete the payment via electronic payment methods. After that, the e-fulfillment center will receive the orders in the picking list from their own warehouse management system. Each type of items are stored in the barcode-based bin location so as to improve its picking accuracy and efficiency. The packed items are then temporarily stored in the staging area, and the delivery routing is then planned to optimize the transportation efficiency and maintain high service level.

B. Existing problems in ABC Limited

Apart from the general handling process for e-commerce orders, the case company is facing challenges in handling perishable food. In the world of e-commerce, the customers need to pay in advance for the products, which is different to the traditional practice, for example buying items from a supermarket or wet market. The customers cannot view or touch the items on hand, and they can only rely on the product description shown on the platform, and the corresponding rating and commenting system for evaluating the description accuracy. In addition, perishable food is highly sensitive to ambient conditions, and its quality and shelf life can be affected by fluctuation of the ambient temperature and relative humidity. In such situations, the e-commerce platform and e-commerce logistics services can easily cause a loss of customer confidence and is damaging to the company reputation. It is because the real-time status of the perishable food is currently not visible and open for the public. If they receive spoilt or deteriorated food, they will complain and leave negative comments in the e-commerce platform. This fosters the negative atmosphere in the eco-system of PFEC. Therefore, the real-time monitoring and transparency on shelf life management are of utmost importance for the e-commerce environment. Without that, customers are not able to get the updated transit information regarding the environmental conditions, and know the customized expiry date for the specific perishable food. Overall, the eco-system of PFEC can be impacted, and the trust and confidence for the e-commerce platform in handling perishable food will be lost.

C. Implementation of ISLMS

The proposed system, i.e. ISLMS, was implemented in the case company as the pilot study to evaluate its feasibility and performance for improving customer satisfaction in the PFEC business. As shown in Fig. 3, the entire implementation is divided into four stages, namely (i) formulation of IoT monitoring system, (ii) determination of fuzzy rules and membership functions, (iii) execution of fuzzy logic approach for adjusting shelf life, and (iv) formulation of quality degradation model, with their corresponding expected output. Consequently, the proposed system is then systematically executed in the case company.

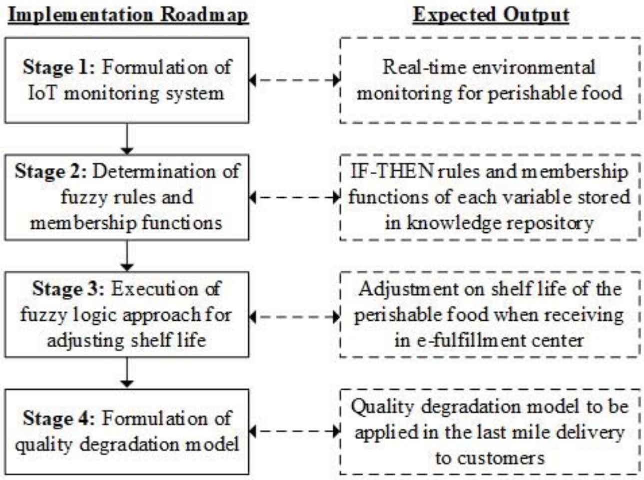

Fig. 3. Implementation roadmap of ISLMS

1) Formulation of IoT monitoring system

In stage 1, the IoT monitoring system needs to be ready for collecting real-time environmental conditions for the packed perishable food. To set up the IoT monitoring system, there are basically three major layers, i.e. physical layer, connectivity layer and application layer, so as to standardize the whole structure of the IoT framework, as shown in Fig. 4. In the physical layer, the SensorTag CC3200 is selected in this study, which is manufactured by Texas Instruments, and seven sensors are embedded, namely ambient light sensor, infrared thermopile sensor, humidity sensor, series reed sensor, digital microphone, nine-axis motion tracking sensor, and barometric pressure sensor. The sensors are attached to two areas, namely (i) the storage area in the e-fulfilment centre, and (ii) the parcels for perishable food. The storage area is the zone-level monitoring for the perishable food, which means the sensor network deployment considers the entire storage facility instead of each batch or lot of perishable food. However, for those picked and packed parcels, the sensors are attached to each parcel so as to monitor the change of environmental conditions during the delivery process. The collected data is then sent to an edge router via the WiFi network using IEEE802.11 b/g/n mode. Through the edge router, the collected data can be standardized and is able to be transmitted to the PaaS based IoT development platform in the connectivity layer. The transmission between edge router and IoT development platform is done by the GSM/3G/4G/LET network, dependent on the required transmission performance. All the data are then stored and managed in the IoT development platform, such as IBM Cloud. Together with the use of node-red and IoT tools, the system prototype is established with the IDCM, FSLMM and QDM modules. The PaaS development platform provides the flexibility in system development and adaptability of multiple programming languages. Thus, the IoT monitoring is then formulated for further data analytics processing.

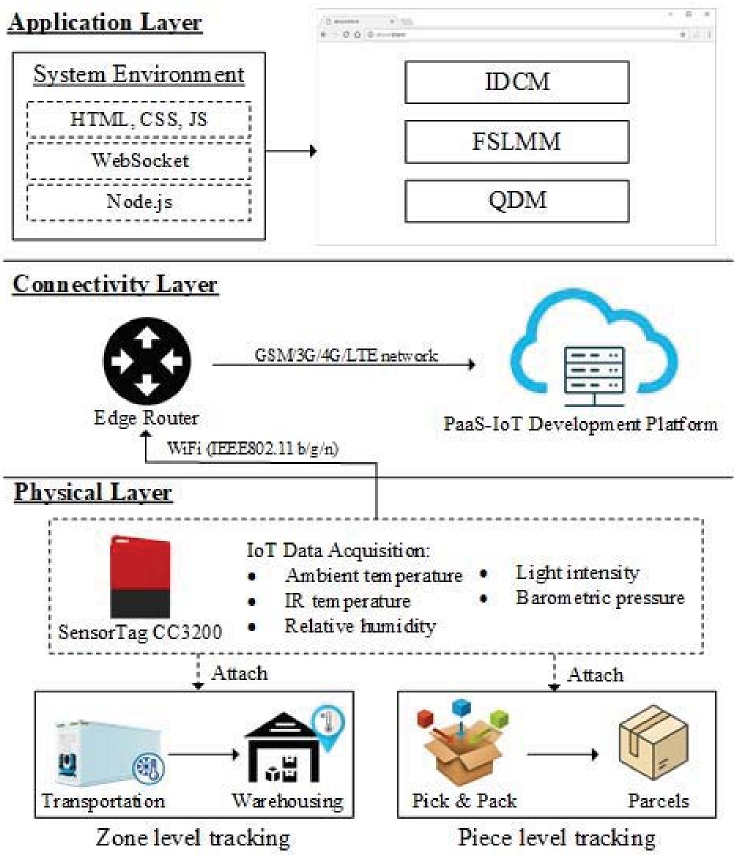

Fig. 4. IoT framework for ISLMS

2) Determination of fuzzy rules and membership functions

In stage 2, before applying the fuzzy logic approach in shelf life management, the fuzzy rules and membership functions for the input and output variables need to be defined in advance. According to FSLMM, the input and output variables are illustrated, and there is a need to define their membership functions and the IF-THEN rules between them. Table I shows the mathematical definition of the membership functions for the fuzzy logic in ISLMS. There are five input variables and three output variables in total. The membership functions are defined by the specific fuzzy classes, ranges and function types. In the case company, the lack of flexibility in food shelf life and the quality deterioration model leads the inaccurate shelf life estimation and a poor quality degradation evaluation. Therefore, fuzzy logic is needed to customize the shelf life and quality degradation model for each batch/lot of perishable food when received at the e-fulfilment center. Without that, the customers cannot have accurate and updated shelf life information, and the logistics company may wrongly plan the delivery routes, leading to spoilage and deterioration of perishable food. On the other hand, the IF-THEN rules between the input and output variables are determined by domain experts for processing in the Mamdani's inference engine. The example rule is as "IF MKAT is High, MKRH is High, Total transit time is Long, Sensory Score is Low, Order frequency is High, THEN Shelf life adjustment is Significantly increase, Deterioration rate is medium, and Deterioration order is First order".

TABLE I. MEMBERSHIP FUNCTIONS FOR FUZZY LOGIC IN ISLMS

Variable(s)	Abbr.	Fuzzy Class	Membership function	Type
Input				
MKAT (°C)	mkat	Low	[0, 0, 5, 10]	trapmf
		Average	[5, 10, 25, 35]	trapmf
		High	[25, 35, 50, 50]	trapmf
MKRH (%)	mkrh	Low	[0, 0, 0.3, 0.4]	trapmf
		Average	[0.3, 0.4, 0.6, 0.7]	trapmf
		High	[0.6, 0.7, 1, 1]	trapmf
Total transit time (hour)	t	Short	[0, 0, 5, 10]	trapmf
		Medium	[5, 10, 30]	trimf
		Long	[10, 30, 50, 50]	trapmf
Sensory score (unit)	s	Low	[0, 0, 4, 6]	trapmf
		High	[4, 6, 10, 10]	trapmf
Order frequency (time)	of	Low	[0, 0, 20, 30]	trapmf
		High	[20, 30, 50, 50]	trapmf
Output				
Shelf life adjustment (%)	sla	Significant decrease	[-1, -0.5, 0]	trimf
		No Change	[-0.5, 0, 0.5]	trimf
		Significant increase	[0, 0.5, 1]	trimf
Deterioration rate (k)	k	Low	[0, 0, 40, 80]	trapmf
		Medium	[40, 80, 120]	trimf
		High	[80, 120, 150, 150]	trapmf
Deterioration order (n)	n	Zero order	[0, 0, 1]	trimf
		First order	[0, 1, 1]	trimf

3) Execution of fuzzy logic approach for adjusting shelf life

The aforementioned membership functions and fuzzy rules are stored in the knowledge repository for use in the fuzzy logic approach in stage 3. The fuzzy logic approach is done in the environment of MATLAB fuzzy logic toolbox to demonstrate the performance and results of the proposed work. In this pilot study, one batch of the perishable food, i.e. premium golden apples, is selected. Before reaching the e-fulfilment center, the mean kinetic ambient temperature is 32°C, the mean kinetic relative humidity is 65%, total transit time is 25 hours, sensory score is 5, and historical order frequency from the e-shop per month is 25 times. After applying the fuzzy logic approach, it is found that the actual shelf life should be reduced 50%, the deterioration rate is 48.1, and the deterioration order is 0.571, as shown in Fig. 5. The proposed approach has a high ease of use in obtaining customization in shelf life adjustment and quality degradation model formulation. It is implied that the food quality is affected due to the poor environmental conditions during the transit before reaching e-fulfilment center. Thus, the shelf life should be decreased, while the quality degradation model is modified to fit the actual situation of the perishable food.

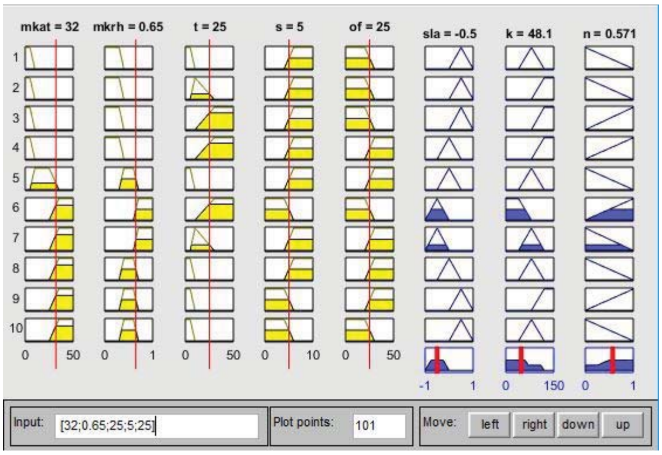

Fig. 5. Results of fuzzy logic approach in ISLMS

4) Formulation of quality degradation model

In stage 4, the quality degradation model can be simply formulated according to the obtained deterioration rate and order from stage 3. Since the deterioration rate is 48.1 and the deterioration order is 0.571, equation (6) can be derived into equation (7) to express the relationship between food quality and time at the constant environmental conditions, where Q_0 is the initial food quality, Q is the obtained food quality ,and t is the specific time. As a result, the users, including the staff in the logistics company and the end customers, can easily access the quality of the perishable food. From the perspective of the end customers, the quality deterioration model can be displayed in the graphical method so as to enhance its readability and ability to be understood. With the aid of this model, it is able to enhance the supply chain visibility and the customer confidence for purchasing the perishable food. Thus, the eco-system of the PFEC can be maintained in a sustainable manner.

$$Q^{0.429} = (0.429 \cdot 48.1)t + Q_0^{0.429} \quad (7)$$

V. Results and Discussion

In this section, the results obtained from the case study are analyzed in performance aspects and advantages in the industry.

A. Performance of the adoption of ISLMS

For the selected batch of perishable food in the case study, the results obtained from ISLMS are positive to the ABC Limited in improving the visibility, transparency, and customer confidence in PFEC. In order to evaluate the performance of the proposed system, the system dashboard is given to the end customers who purchased the selected perishable food in the e-commerce platform. This group of customers is then invited to participate in the survey to examine their needs and comments on the proposed system, while another group of customers who purchased the same items without using the proposed system is set up as the control group. In the 1-month implementation period, it is found that customer satisfaction on the delivery services using the proposed system has an increase of 52.3%, and confidence in the purchased perishable food is increased by 36.1%. Over 70% of the customers are satisfied with the additional monitoring and traceability functions for the shipment tracking system. Therefore, it is concluded that the performance and value of the proposed system is validated. The proposed system is thus valuable and can be extended to other perishable food handled in the e-fulfilment center, so that the shipment tracking system provided to the customers does not only include the timestamp and latest shipment status, but also the real-time monitoring and shelf life management.

B. Advantages of adopting ISLMS

After implementing ISLMS in ABC Limited for one months, it is found that there are two major advantages, namely (i) enhancement of customer satisfaction and confidence, and (ii) improvement of incident management and operation management.

1) Enhancement of customer satisfaction and confidence

In the past, customers who purchased items from the e-shop are able to track and trace the latest shipment status through the tracking platform, such as afterhip.com. The tracking information provides the customers with the actual shipment status and expected shipment arrival. However, such tracking platform is insufficient for handling the perishable products. Apart from the shipment status and timestamp, customers also want to have the real-time environmental monitoring and shelf life management. With the use of proposed system, the traditional tracking platform can be further enhanced by integrating IoT technologies and AI techniques to strengthen the environmental monitoring, shelf life determination and degradation model. In this way, the customers are able to view all the corresponding information from the tracking platform so that they are more confident in purchasing perishable food from the e-shop with the proposed system. Moreover, they are satisfied in viewing the historical monitoring data for the delivery process so as to ensure that no spoilage and deterioration is occurred.

2) Improvement of incident management and operation management

From the operational perspective, the shelf life is fixed at the food processing center without consideration of the fluctuation of temperature and relative humidity between the food processing center and end customers. The fixed shelf life may not actually reflect the product quality. Without proper management, it may impact on the company's reputation in handling perishable food, and the sales performance can be directly affected. The ISLMS provides the systematical shelf life determination and quality degradation model, and thus it prevents delivery of spoilt food to customers. On the other hand, real-time environmental monitoring is able to improve incident management to avoid temperature excursions in the e-fulfilment center and delivery process. The staff can receive alerts of abnormal environmental conditions, and take corresponding actions to meet the handling requirements of perishable food. Therefore, the proposed system is not only beneficial to the end customers, but also helpful to the logistics company in handling perishable food. They can truly execute the policy of first expired first out (FEFO) in the e-fulfilment center so as to reduce inventory obsolescence. Pro-active actions can be taken to overcome unexpected incidents during the warehousing and transportation process.

VI. Conclusions

The market for perishable food e-commerce is exponentially expanding due to the mature e-commerce business and modern customer buying behavior. In the past, an entire batch of perishable food can be shipped in refrigerated or reefer containers so as to prevent temperature excursions. However, such methods are not applicable in the e-commerce business because customers are not going to purchase a container of the perishable food, and delivery is to their homes. Moreover, customers are unable to view the actual products on hand before paying for them. In order to overcome the above challenges and further strengthen the supply chain visibility in PFEC, a new system, i.e. ISLMS, is developed. IoT technologies are applied to establish the real-time environmental monitoring for zone-level and piece-level tracking for the warehousing and transportation respectively. The collected data are then stored for the shelf life adjustment and quality degradation model formulation. Fuzzy logic is applied to consider the environmental conditions, sensory score and order frequency to determine shelf life adjustment, deterioration rate and deterioration order. In applying the Arrhenius equation, the quality degradation model can be formulated for a specific batch or lot of perishable food. In order to validate its feasibility and performance, a pilot study was conducted in ABC Limited, and it was found that customer satisfaction and confidence were improved. In addition, it has positive influence on incident management and operation management in PFEC. It is therefore proven that the ISLMS is a feasible method to improve the environmental monitoring and shelf life management in handling perishable food. In order to further improve the proposed system, future research can be conducted in the intelligent methods used in fuzzy logic and additional operational variables in the shelf life management can be considered.

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