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Integrating wireless sensor networks with statistical quality control to develop a cold chain system in food industries

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ABSTRACT

Cold chain management is of importance for manufacturers in the food industry since they face the dilemma of having to choose between frozen storage and cool storage in delivering products to retailers or end-consumers. Frozen storage incurs high-energy consumption for the preservation of food products, whereas cool storage involves the constant threat of bacterial decay. Contemporary cold-chain development in temperature control usually focuses on single logistic chain rather than serving multiple channels. In order to overcome the aforementioned deficiency, this study proposes a time-temperature indicator (TTI) based cold-chain system, which uses wireless sensors for collecting temperature data and implements the formulation of Critical Control Point (CCP) criteria throughout the entire delivery process. In particular, this approach is based on an Internet-of-Things (IoT) architecture as well as international food standards named ISO 22,000. More importantly, four new business models including (1) cold chain home-delivery service; (2) Convenience store (CVS) indirect delivery; (3) CVS direct delivery; (4) flight kitchen service, are successfully developed for conducting performance assessment. Experimental results indicate that the proposed framework can increase annual sales of braised pork rice from 4.44 million bowls to over 6 million bowls, create more distribution channels to increase extra revenue of more than US$6.35 million, and reduce 10% energy consumption in central kitchens to enhance turnover of electricity from US$14.23 raised to US$18.64 per kilowatt hour.

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1. Introduction

The Internet of Things (IoT) is a growing trend with a powerful influence in shaping the development of the information and communication technology (ICT) sector. Today, the IoT encompasses a wide variety of items used in our daily lives, including radio frequency identification (RFID) tags, sensors, actuators, and even smart devices like mobile phones. A unique addressing scheme enables these objects to communicate and interact with other items to achieve common goals [1,4,10,13,23,26,30,31]. In practice, the IoT is expected to develop in areas such as wireless sensor networks with the aim of collecting contextual data [29,43,44]. Progress is also being made in service-oriented architecture (SOA) [18], which is a software approach to expanding web-based services using the capabilities of IoT (Web of Things, WoT) [14].

Developments in the IoT will no doubt lead to new services applicable to all facets of our lives. From a system-level perspective, IoT can be viewed as a highly dynamic and radically distributed networked system comprising a large number of smart objects and the information they collect [7]. In contrast, from a service-level perspective, the IoT is fundamentally a means of integrating or composing the functionalities and/or resources provided by smart objects. In many cases, this integration is in the form of data streams [6,16,19]. However, from a user perspective, the IoT makes it possible for new services to be developed in response to the needs of users for use in everyday activities [39].

As we know, cold chain management (CCM) is used to optimize the freshness and safety of food products [11]. Currently, manufacturers in the food industry face the dilemma of having to choose between using frozen storage and cool storage. This issue is relevant in all stages, including cooking, cooling, freezing, delivering, and storage. Frozen storage incurs high-energy consumption for the preservation of food products, whereas cool storage involves the constant threat of bacterial decay. Contemporary developments in temperature control tend to focus on single logistic chain rather than serving multiple channels simultaneously. This type of business model obviously confines the range of options with regard to food supply and often makes it impossible to meet the complex requirements of the food industry. Although frozen storage can reduce the constant threat of bacterial decay, but it will bring a lot of shortcomings, such as high-energy consumption, taste deteriorates due to residual ice, and the number of sale channel is limited. Under strict temperature monitoring, switching a number of products from frozen storage to cool storage seems to be feasible to improve the shortcomings mentioned above.

Again, temperature is the main post-processing parameter in the determination of shelf-life in a cold chain of chilled and frozen food products. This study developed an innovative cold chain time–temperature indicator (TTI) system, which uses wireless sensors for collecting temperature data and formulating Critical Control Point (CCP) criteria. Then, $\overline{X}$–R control charts are formulated for monitoring each point in

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the process. This approach is based on an IoT architecture and international food standard (ISO) 22,000. In particular, the proposed methodology was applied to a prestigious food franchise in Taiwan to evaluate its efficacy. The proposed IoT solution employs sensors to collect temperature data at each point in the process for later ISO 22000/HACCP standard CCP criteria. Analysis of the collected data facilitates decision-making process regarding frozen and cool storage.

In practice, changes in storage procedures can reduce energy consumption and expand the number of selling channels, which may otherwise be subject to the limitations inherent in using only one form of cooling. In addition, changes in food storage can lead to changes in conventional business models in the food industry, such that food manufacturers have been able to include restaurants, catering services (even in airplanes), convenience stores, and home delivery services among their potential clients. These changes have considerable potential in enhancing brand value. The IoT also makes it possible to address environmental concerns by reducing energy costs. In summary, the main contributions of this study are highlighted as follows:

- *An industrial case in which the process is transformed from frozen storage to cool storage is implemented to take food taste as well as food quality into account.*
- *A time-temperature indicator system via using wireless sensors enables a service-oriented architecture to achieve innovative cold chain management.*
- *New business models in the food industry, such as (1) cold chain home-delivery service; (2) Convenience store (CVS) indirect delivery; (3) CVS direct delivery; (4) flight kitchen service, are generated and assessed for benchmarking.*

The remainder of this paper is organized as follows. Section 2 and Sections 3 outlines the existing cold chain service models and the proposed cold chain system, respectively. Section 4 develops four new business models and demonstrates performance analysis of the case company for validity justification. Lastly, concluding remarks are drawn in Section 5.

2. Literature review

In this section, two important areas in food process management are briefly overviewed, such as cold chain management (CCM) and statistical process control (SPC). The former issue, CCM, is related to our domain problem (i.e. replacing frozen storage by cool storage) whereas the latter issue, SPC, is a quantitative method used to justify whether the operational process (including production and logistics) is in control or not in a systematic manner.

2.1. Cold chain management

Supply chains are defined as systems with four fundamental tasks: planning, sourcing, producing, and delivery [50]. Supply chain management (SCM) requires that special attention be paid to products with a limited shelf life as well as those that require special equipment and facilities for sale, storage and distribution. This led to the emergence of cold chain management (CCM). In [3], CCM is defined as the process of planning, implementing, and controlling the efficient, effective flow and storage of perishable goods, and related services and information from one or more points of origin to production, distribution and consumption. CCM integrates logistics related to perishable goods into an existing business process for the creation of customer value [49]. CCM is used for managing activities associated with the transport and storage of perishable products, such as medicine, blood, dairy, meat, food, vegetables, mushrooms, flowers, and fruit products. These perishable items must be distributed within a specified time and held under particular environment conditions [32,37,45,51]. Monitoring in every stage of the cold chain (CC) is required to prevent the spoiling of perishable products.

According to reports published in several countries, a failure to keep perishable items in a suitable environment or ensure on-time delivery to customers ultimately leads to a waste of resources. For instance, fruits and vegetables totaling 75,000,000,000 Yuan deteriorate in storage and delivery each year in China. This 370,000,000 t of vegetables and fruits could be used to feed 200,000,000 people [32]. In India it is estimated that approximately 35–40% of the total production of fresh fruits and vegetables is wasted due to inadequate monitoring, poor logistics, ineffective CC facilities at retail points, and a lack of infrastructural support [46]. The need to address this high rate of waste was the motivation for this paper.

Several researchers have addressed the issue of CC from various perspectives. Most studies have dealt with temperature monitoring in food throughout the CC, in order to obtain a time–temperature history of the products [15,22]. Some of these studies have also dealt with the monitoring of quality, particularly with regard to microbial evolution. Derens, Palagos, and Guilpart [8] identified three types of refrigerated products that require monitoring throughout the cold chain: fresh meat, meat products, and yogurt. They placed small temperature recorders within food products at the end of the production line (prior to dispatching the product along the supply chains). Their results indicate that temperature control is particularly critical in the final three stages of the cold chain, namely, display cabinets, transport after shopping, and domestic refrigerators.

Landfeld et al. [33] investigated the time–temperature history of perishable foods after shopping and during home refrigerator storage. Monte Carlo simulation showed that 27.3% of the product would exceed the critical microbial load. Data analysis has shown that storage time and the temperature in the domestic refrigerator are the main factors associated with the growth of pathogens. Jevšnik et al. [27] underlined several gaps in food safety knowledge and practices associated with shopping and eating. In their study, temperature in the retail cold chain was identified as the least important parameter from the perspective of consumers. Table 1 briefly summarizes the recent researches in the area of the CCM. In food supply chains, temperature conditions have a substantial impact on the risk of spoilage, the shelf life of the products, and ultimately even the quality of the end product [37]. There are five categories of foods that require careful monitoring and temperature control. These include hot food (above 60 °C constantly), fresh food (18 °C constantly), cold food (0 °C to +7 °C), chilled food (−2 °C to +2 °C), frozen food (below −18 °C), and deeply frozen food (below −30 °C).

2.2. SPC in the food industry

In recent years, the importance of quality amongst food technologists and food producers has dramatically grown, mainly due to stricter consumer expectations, governmental regulations and fierce market competition. In response to such demands, the food industry began to seek solutions using quality control and quality improvement techniques. Thus, more and more studies have adopted the technique named Statistical Process Control (SPC). Quality control in the food industry is closely related to technology, sensory (flavor, color, texture, smell and taste) and physical attributes, safety (microbiological), chemical make-up and nutritional value [9]. Food poisoning or microbiological outbreaks have become the biggest concern for food producers, and thus, governments and consumers now pay more attention to the quality of food [16,35,36].

Continuous rejection of finished goods, product scrapping, and product recalls have led to serious financial implications and put a firm's image and public trust at risk [9,35]. In addition to customer perceptions of the quality of a product, the food industry has faced the need to consider critical factors in the production process, the distribution processes, and product-market systems as indicators of quality overall [40,42,48]. This also introduced and strengthened a trend observed over the last decade among western retailers towards quality certifications, such as Hazard Analysis and Critical Control Points (HACCP), International

Table 1
A summary of representative studies in the area of CCM.

Title of research	Purpose
The cold chain of chilled products under supervision in France[8]	The study identified three types of refrigerated products that require monitoring throughout the cold chain. The results indicate that temperature control is particularly critical in the final three stages of the cold chain, namely, display cabinets, transport after shopping, and domestic refrigerators.
Consumers' awareness of food safety from shopping to eating[27]	The study underlined several gaps in food safety knowledge and practices associated with shopping and eating. In this study, temperature in the retail cold chain was identified as the least important parameter from the perspective of consumers.
Time temperature histories of perishable foods during shopping, transport and home refrigerated storage[33]	The study investigated the time-temperature history of perishable foods after shopping and during home refrigerator storage. Data analysis has shown that storage time and the temperature in the domestic refrigerator are the main factors associated with the growth of pathogens.
A new benchmarking approach in cold chain[46]	The research is to develop a linear pair model for selecting the best sales agents as a "Benchmark" in the presence of non-discretionary factors and imprecise data under free disposability assumption.
Experimental investigation and modeling in the food cold chain: Thermal and quality evolution[32]	The study combined deterministic and stochastic modeling in food processing and the cold chain. This review provides an insight into the background, problematic and transfer mechanism of food refrigeration.
Evaluation of the cold-chain for oral polio vaccine in a rural district of India[43]	The study was designed to evaluate the cold-chain equipment in a rural district of central India. In this article, the study presents data concerning the compliance of equipment and temperature maintenance at each level (i.e., type of health center) of the cold chain in the rural district.
Study of countermeasures relating to developing food cold chain logistics [51]	The study analyzed the present situation and the problems of cold chain logistics. It also put forward some countermeasures of developing cold chain logistics in China.

Organization for Standardization (ISO), British Retail Consortium (BRP), European Retail Good Agricultural Practices (EUREP-GAP), and Safe Quality Food.

Simply speaking, statistical methods that have been accepted as an important approach in quality control in the food industry started from 1950s. The concept of quality assurance was proposed in the 1970s by food processors and public sectors and it was believed as the best remedy to solve the quality issues faced by the food industry. One of the major points, especially in the USA, was the establishment of the Food Products Safety and Consumer Protection Act. By achieving this, an integrated quality system like Good Manufacturing Practice (GMP) was suggested and proposed [24,47]. In 1986, the American Society for Quality Control (ASQC) published the Food Processing Industry Quality Systems Guidelines outlining the basic elements for structuring and evaluating the systems required for food production. Later, Total Quality Control (TQC) was introduced after a long-range research programmer conducted in Norway [41].

In the 1990s, several major food-borne illness outbreaks and resulted in awareness of that effective control of food safety should be the most critical activity in food production. Therefore, HACCP and SPC were put in practice in an integrated manner to improve the effectiveness of food quality control systems. Additionally, the utilization of SPC has facilitated HACCP applications to control and monitor process in real time [16,20]. After the millennium years, quality control studies in the food industry have diverted its direction to nurturing a statistical thinking mindset [17,21]. Obviously, it is necessary for top management as well as all employees to understand the benefits of quality control and improvement. The culture of continuous improvement and statistical thinking has set a new perspective in the food industry, where quality control and improvement activities are not only useful at the production line but also in the other business units across the organization. For convenience, Fig. 1 illustrates the evolution of SPC in the food industry [34].

In summary, SPC implementation in the food industry is inspired by two categories of motivational factors, namely, proactive (self-desire originated from food producers) and reactive (responds to regulations and threats to reduce adverse effects) [17]. Specifically, the obligation of food producers to comply with food safety, food law, and regulations has been thoroughly addressed [28]. Based upon the Pareto 80/20 rule, 20% (vital few) of the factors should be systematically identified and extracted. In Fig. 2, obviously, 67% of the vital few factors consist of proactive factors while the remaining 33% arises from reactive factors. In particular, the greatest motivation for SPC implementation is "reducing process variability" (cited by 16.7%) followed by the national legislation demands on assurance of product safety and then the second is "correct weight and measurement" of food products (cited by 11.1%) [34].

To the best of our knowledge, no previous study has proposed replacing frozen storage with cool storage. In [37], predictive microbiology made it possible for researchers to model food safety and quality while taking the effect of temperature into account, the intrinsic characteristics of the product, and the packaging environment. Cold storage is essential for fresh products to minimize the risk of food-borne illnesses, to blunt physiological activities, and to preserve quality. This study applied a wireless sensor network to develop an innovative CCM system for cool storage (−2 °C to +7 °C), particularly for handling fresh products.

2.3. Proposed cold chain framework

The food industry is predicated on the principles of rapid service, convenient ordering, timely preparation, and fast checkout. However, fulfilling these criteria can be quite challenging, particularly when dealing with the diversity and complexity of Chinese cuisine. The producers of Chinese food constantly struggle to provide delicious food of high quality in a timely manner. Here, we adopted the IoT framework to establish of a novel cold chain management system for a case study of Chinese food producers, which includes processing, storage, sorting, delivery, unloading, retail storage, and even the final step of reheating the products. As shown in Fig. 3, the cooling storage system comprises (1) analyzing the possibility of converting products from frozen storage to cooling storage, considering issues related to the central kitchen, cool storage, logistics, and retail sales, (2) formulating CCP criteria in terms of $\overline{X}$–R control charts for monitoring each point in the process, and (3) developing a cold chain system that includes temperature monitoring using various types of wireless sensor associated with warning mechanisms to ensure precise control over the temperature of products.

2.4. Empirical analysis of frozen storage and cool storage

Branch outlets of the company in our case study produce a number of side dishes, such as rice and boiled green vegetables while a central kitchen supplies the main menu items. Prior to storage, products supplied by the central kitchen are categorized as either frozen storage products or frozen storage semi-manufactured products. Fully-cooked products, such as braised pork, must be thawed and reheated prior to serving. Partially-cooked products, such as shrimp rolls, are generally

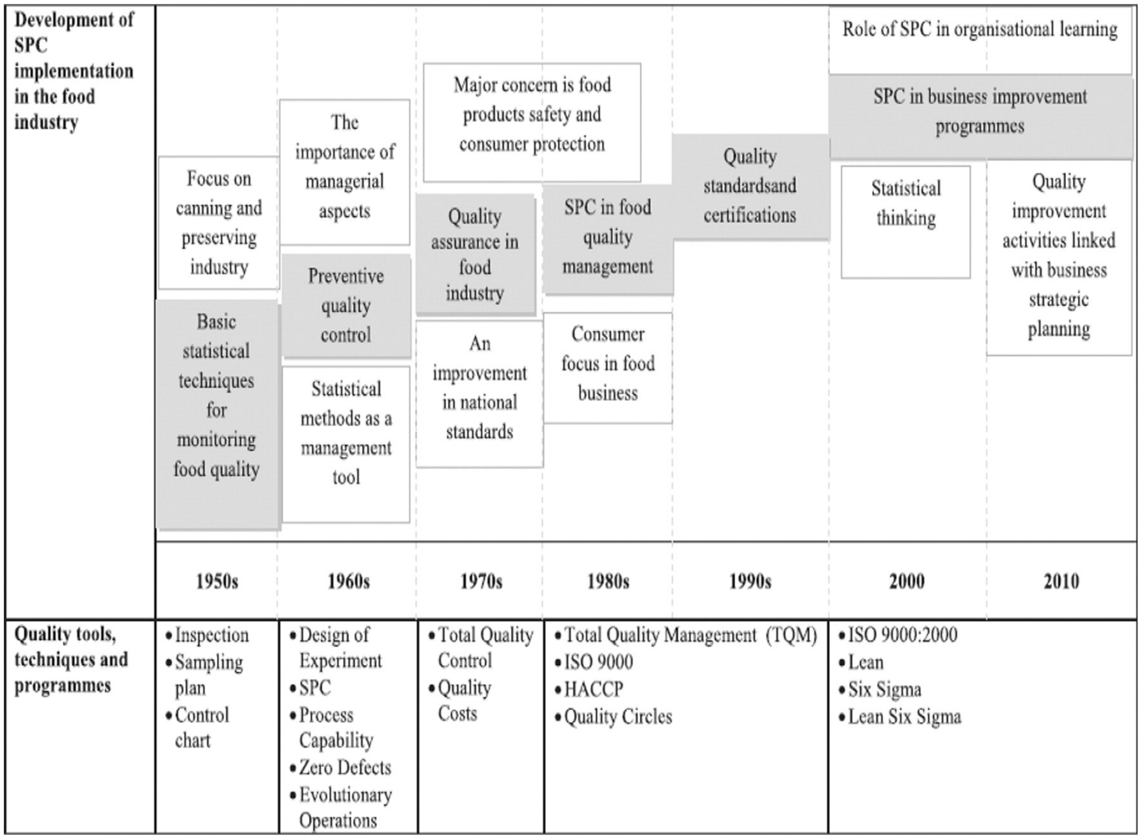

Fig. 1. Development of implementing SPC in the food industry [34].

thawed and then fried prior to serving. Both classes of frozen item are potential candidates for cool storage. Table 2 presents the criteria used to determine ten items generally found in frozen storage should be reclassified to the category of cool storage. According to experts' suggestion and microbiological challenge testing, this study evaluated twenty one items [5] to determine which category of storage would be the most efficient.

2.5. Formulation of CCP criteria

Our aim was to build a system capable of providing a comprehensive history related to the temperature of products using a cross-logistic model rather than a single-logistic model. The objective was to expand on the conventional approach in which the temperature of products is tracked only in vehicles with a single-temperature zone.

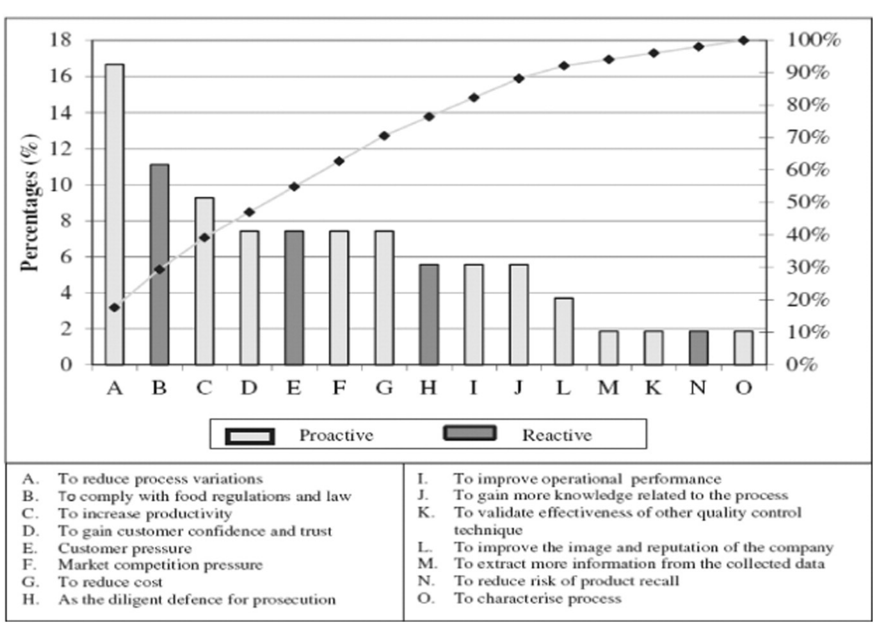

Fig. 2. Motivations of implementing SPC in the food industry [34].

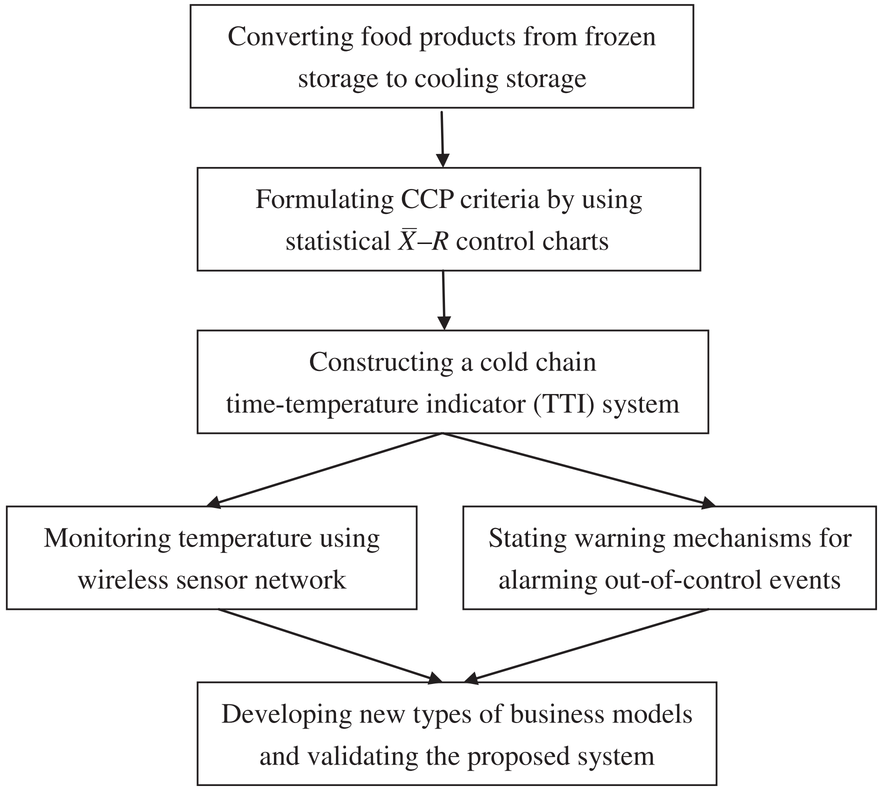

Fig. 3. The proposed research framework.

Modern quality and safety assurance systems are based on eliminating failures related to quality and safety through monitoring, recording, and controlling of critical parameters during the entire life cycle of the product, including the post-processing phase and even extending to the time of use by the final consumer. The International Food Safety Standard, ISO 22000/HACCP, designates a critical control point (CCP) for each of the main stages in the preparation/distribution process, including food processing (cooking), sterilization, cooling, chilling, delivery and re-cooking. Fig. 4 presents a diagram outlining this process.

Control charts are tools used to measure, analyze, and control the various phases of a producing process. Control charts are used to determine whether a process is in a statistical control state and establish control limits for monitoring it in the future. Control charts can be used for quantifying process outputs and investigating whether this can remain

Table 2
Analysis of products in frozen storage and cool storage.

Category	Product	Planned for Cool storage	Unsuitable for frozen storage	Unsuitable for cool storage	Footnote
Rice	Braised pork rice	○			Braised pork
	Chicken rice	○			Shredded chicken
Vegetables	Stir-fried bean sprouts		○		➢ Bean sprouts are prone to become frost-bitten during freezing process. ➢ Delivered by suppliers right to the stores for further processing.
	Braised shredded bamboo shoots	○			
	Boiled green vegetables		○		Same as bean sprouts
Meat or Seafood	Braised tendon	○			
	Shaoxing drunken chicken		○		Unfreezing makes it easy to lose flavor.
	Tangshan pork ribs			○	Preserved raw products.
	Fried Chicken			○	Preserved raw products.
	Shrimp roll			○	Unfreezing process induces juice to exude from the raw products.
	Braised pork knuckle	○			
	Braised pork hock	○			
	Mixed shrimp rolls and sausages			○	Shrimp rolls are raw products. Unfreezing process induces juice to exude from the raw products.
	Stone plate salted pork			○	Preserved raw products.
Soup	Bitter gourd and pork rib soup		○		This soup contains rich moisture and the bitter gourd is prone to frost-bitten in unfreezing process.
	Four spirited soup	○			
	Dragon marrow soup	○			
	Corn soup	○			
	Meat ball soup		○		This soup contains beetroot which has rich moisture and
	Beetroot soup		○		is prone to become frost-bitten in unfreezing process.
	Daylily pork rib soup	○			

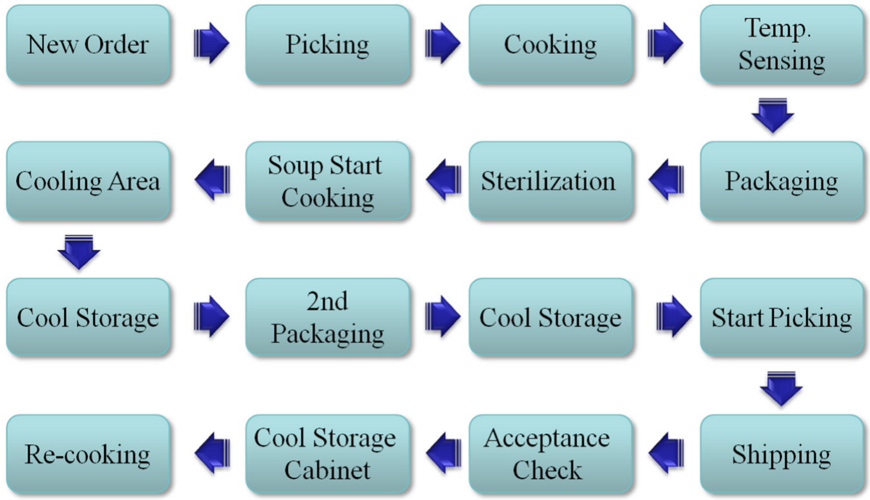

Fig. 4. Critical control point in the whole process.

within statistically defined control limits. In addition, control charts can be used to indicate the beginning of a process shift, which could potentially lead to a safety hazards [25].

We constructed $\overline{X}$–R control charts using temperature profiles of all processes. For each sample, we began by calculating the $\overline{X}$(the mean of the temperature profiles for each subgroup (sample size = 5)) and R (the range of the measurements for each subgroup (sample size = 5)). The control charts comprise the CL: center line of the corresponding control chart; UCL: upper control limit of the corresponding control chart; and LCL: low control limit of the corresponding control chart. Any data point exceeding the control limits indicates a process which is in an out of control state. For the $\overline{X}$ control chart:

$$CL_{\overline{X}} = \frac{\sum_{i=1}^{n} X^{i}_{mean}}{n} \tag{1}$$

$$UCL_{\overline{X}} = CL_{\overline{X}} + A_2 \times CL_R \tag{2}$$

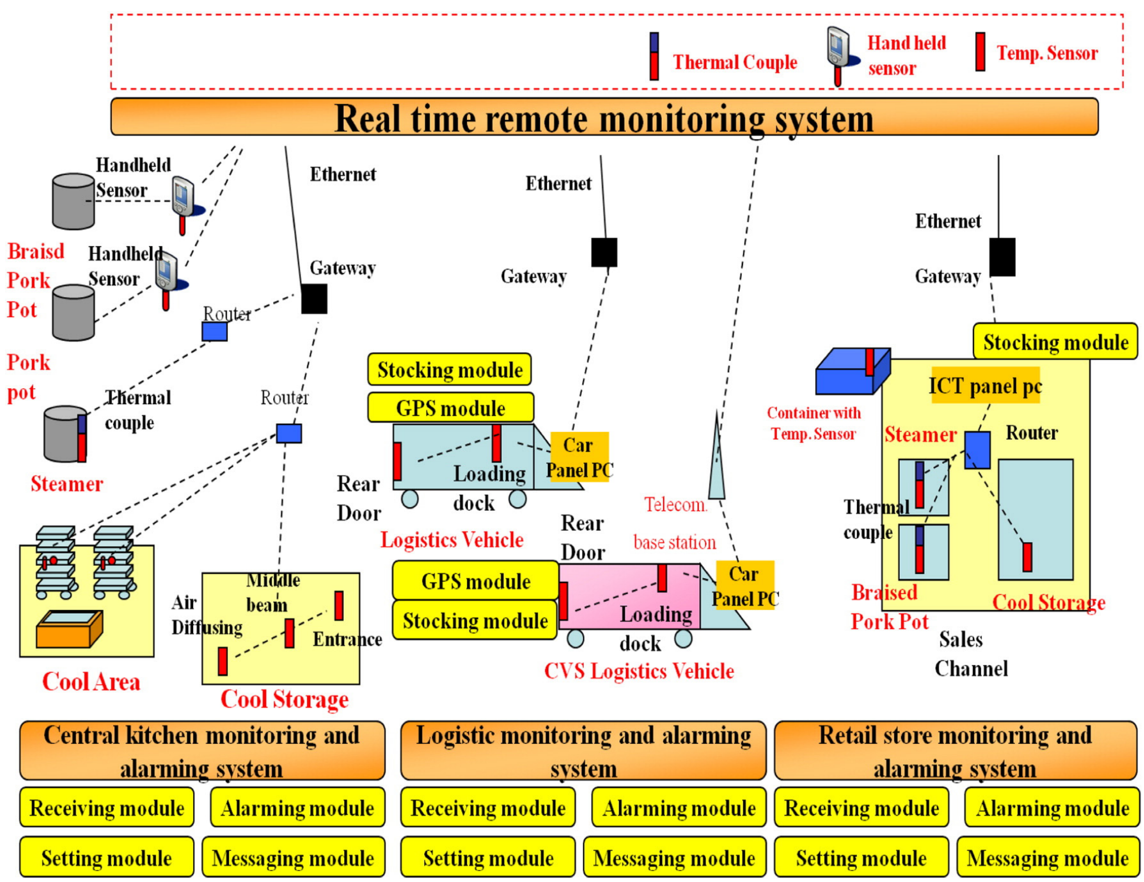

Fig. 5. Real-time remote monitoring system.

Fig. 6. A monitoring and warning system governing temperatures in the cooking of braised pork.

Fig. 7. A scatter plot to display temperature in the process of cooking braised pork.

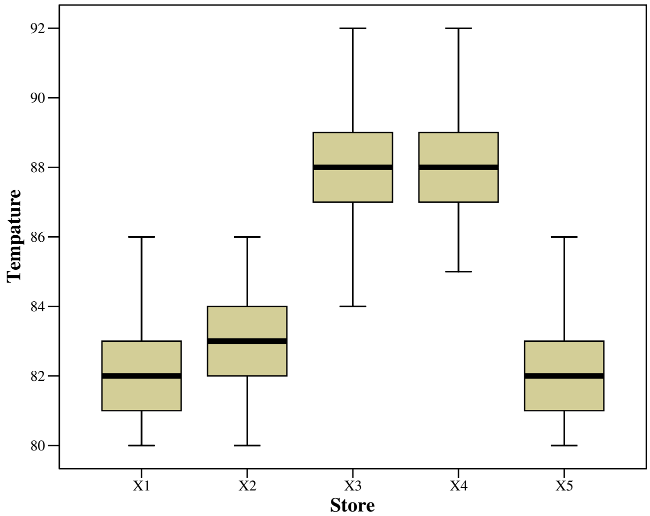

Fig. 8. A Box plot to display temperature in the process of cooking braised pork.

$$LCL_{\overline{X}} = CL_{\overline{X}} - A_2 \times CL_R \tag{3}$$

where A2 is a coefficient equal to 0.58 found in the tables in [45] based on the sample size of each subgroup.

For the *R* control chart:

$$CL_R = \frac{\sum_{i=1}^{n} R_i}{n} \tag{4}$$

$$UCL_R = D_4 \times CL_R \tag{5}$$

$$LCL_R = D_3 \times CL_R \tag{6}$$

where D4 and D3 are coefficient equal to 2.11 and 0 found in the tables in [38] based on the sample size of each subgroup. The rules used to investigate whether a process was in an out-of-control state were: (a) any data point exceeding UCL and LCL; and (b) eight consecutive data points on the same side of the average ($CL\overline{X}$ or CLR).

3. Proposed cold chain system

Generally, ensuring compliance with international food standards can be very difficult in Taiwan because of its high-temperature and high-humidity environmental conditions. The main challenges in this study are learning how to select and implement appropriate wireless sensors to develop a system that could operate reliably in such a tough environment. In terms of the CCP, a real-time remote monitoring system has been developed. In terms of the CCP, a real-time remote monitoring system has been developed. Specifically, 2.4 GHz ZigBee was adopted in the data transmission network for remote monitoring. As shown in Fig. 5, it includes three alarm based subsystems: a central-kitchen monitoring module, a logistic monitoring module, and a retail-store monitoring module.

Here, we outline the international standards, CCP, and temperature monitoring of food products, such as meat/seafood, soup, and others. We use the case of braised pork as a representative example. Samples were randomly collected from five branch stores of the case company, especially temperature data was collected during the entire process (18 days in total). Without loss of generality, temperature data was gathered at two intervals a day, including lunch (10:30–13:30) and dinner (17:00–20:00).

3.1. Central temperature in cooking braised pork

We employed a touch screen to collect information from every client. The data was obtained from the ERP system working list, which provides a selection menu for the staff. When cooking is complete, temperature data can be obtained via wireless sensors, whereupon the staff receives a batch number on the touch screen. An average temperature is later calculated for every client. When the temperature of a product drops below <80 °C, an alarm is triggered and notification is sent to the plant manager, information officer, general manager or other appointed staff members. After resolving the situation, the plant manager sends the message “situation clear” to all other parties involved in the event. Fig. 6 presents a diagram outlining this process.

Fig. 7 is a scatter plot regarding the temperature in the process of cooking braised pork. In particular, the temperature data w.r.t. five branch stores is sampled once per minute and gathered in the lunch time (from 10:30 to 13:30). Thus, there are 180 samples observed in total. Furthermore, Fig. 8 is a box plot to show the spread around the central (average) temperature in cooking braised pork. Although the average temperature are set a little differently with respect to five branch stores, however, these plots indicate that the deviation in temperature is well controlled in a limited range. As we know, controlling mean shift associated with variance spread is critical to improving process capability in practice. In this case, the temperature needs to be controlled above 80 °C to keep a good taste of braised pork rice.

3.2. Ambient temperature

When the temperature of a product fails to cool down to 21 °C in 2 h, an alarm is triggered. Situations are then resolved in a manner similar to that of Case i.

3.3. Temperature of cool-storage warehouse in central kitchen

When the temperature of a product falls out of the specified range (between +7 °C and −2 °C), an alarm is triggered. Situations are then resolved in a manner similar to that of Case i.

3.4. Product temperature in tally process

Client information includes branch and logistic codes related to product temperature in tally process. When temperature records are missing or the temperature of the package falls out of the acceptable range (between +7 °C and −2 °C) an alarm is triggered. Situations are then resolved in a manner similar to that of Case i.

3.5. Product temperature in cabinet delivery and in vehicle delivery

Wireless sensors are used to record the temperature of products in the cabinet during delivery as well as the temperature inside the vehicle during distribution. When temperature records are missing or the temperature of the package falls out of the acceptable range (between +7 °C and −2 °C) an alarm is triggered. Situations are then resolved in a manner similar to that of Case i.

3.6. Temperature of cool storage cabinet in branch stores

Wireless sensors are used to record the temperature of products in the cool storage of branch restaurants. When temperature records are missing or the temperature of the package falls out of the acceptable range (between +7 °C and −2 °C) an alarm is triggered.

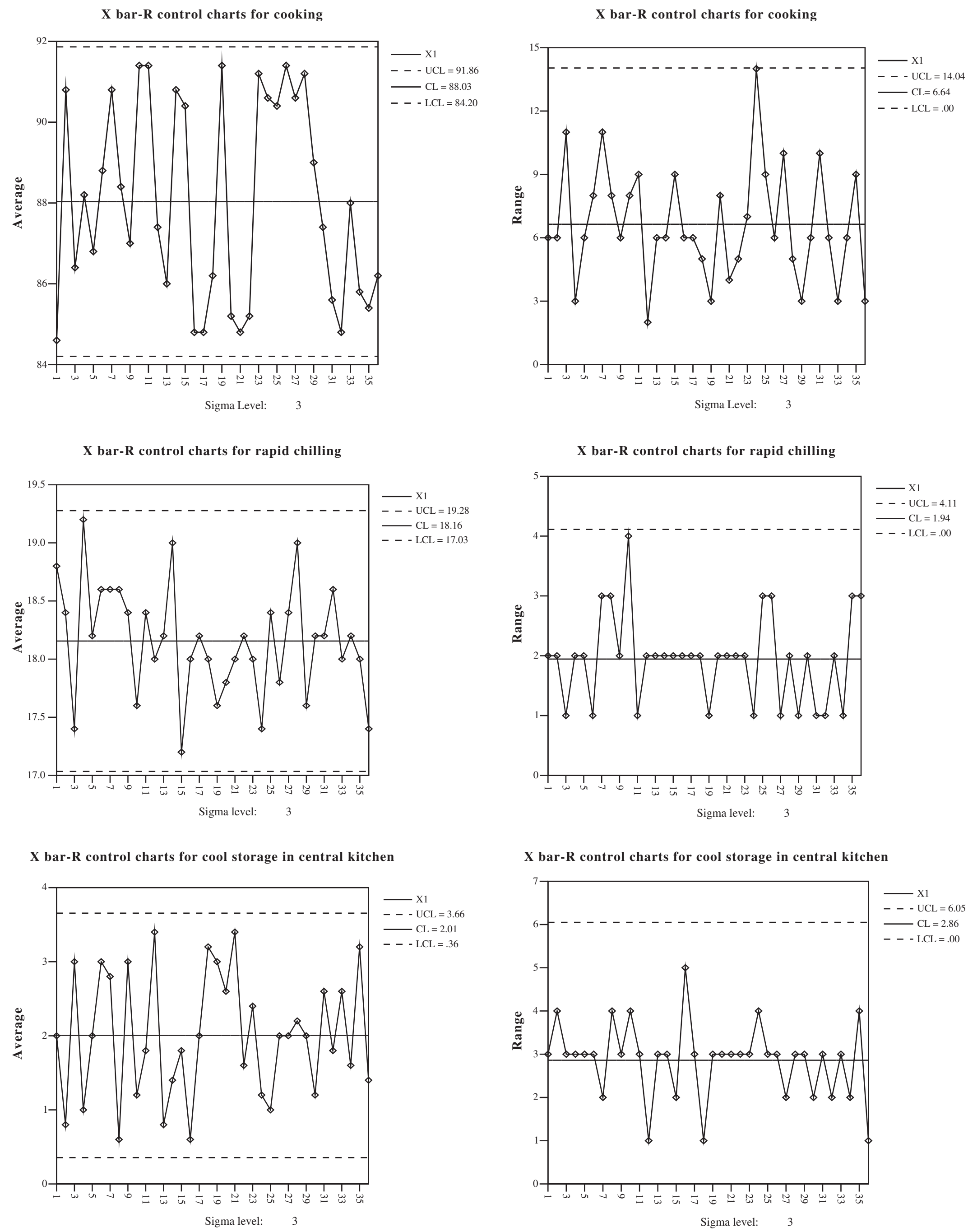

Fig. 9. $\overline{X}$–R control charts for monitoring the temperature of food products in various processes.

3.7. Temperatures in the re-cooking process

Wireless sensors are used to monitor the temperature in the center of products undergoing re-cooking in the dinner time. If the temperature drops below 80°, then an alarm is triggered.

Fig. 9 presents the $\overline{X}$–R control charts to monitor various parameters' temperature in the food products. In terms of $\overline{X}$ (R) chart, a manufacturing process in food components is well controlled by observing the average (range) of the temperature in each process. The sample size of the control chart is determined as follows: with respect to five branch stores, 36 samples have been respectively collected over a period of 18 days. Following a normal distribution (see Eqs. (1)—(6)), a 95% (2.5%–97.5%) confidence interval is set around the average temperature to derive both UCL (upper control limit) and LCL (lower control limit). If an out-of-control state was not observed in these samples, a process can be judged to be in control, especially when a number of products were already switched from frozen storage to cool storage in advance. No particular out-of-control is alerted because all of the observed samples are located between the LCL and the UCL.

In this study, the main operational processes include food processing (cooking), sterilization, cooling, chilling, delivery, and re-cooking. The temperature observed in the production process must be strictly monitored and managed. In practice, the temperature data generated throughout the process is aggregated once per minute via a wireless transmission module and a receiving module. When the temperature is deemed to be out of control, the alarming module immediately sends warning messages via Gmail and SMS to notify responsible staffs. Fig. 10 displays the CCP framework used in the production process of

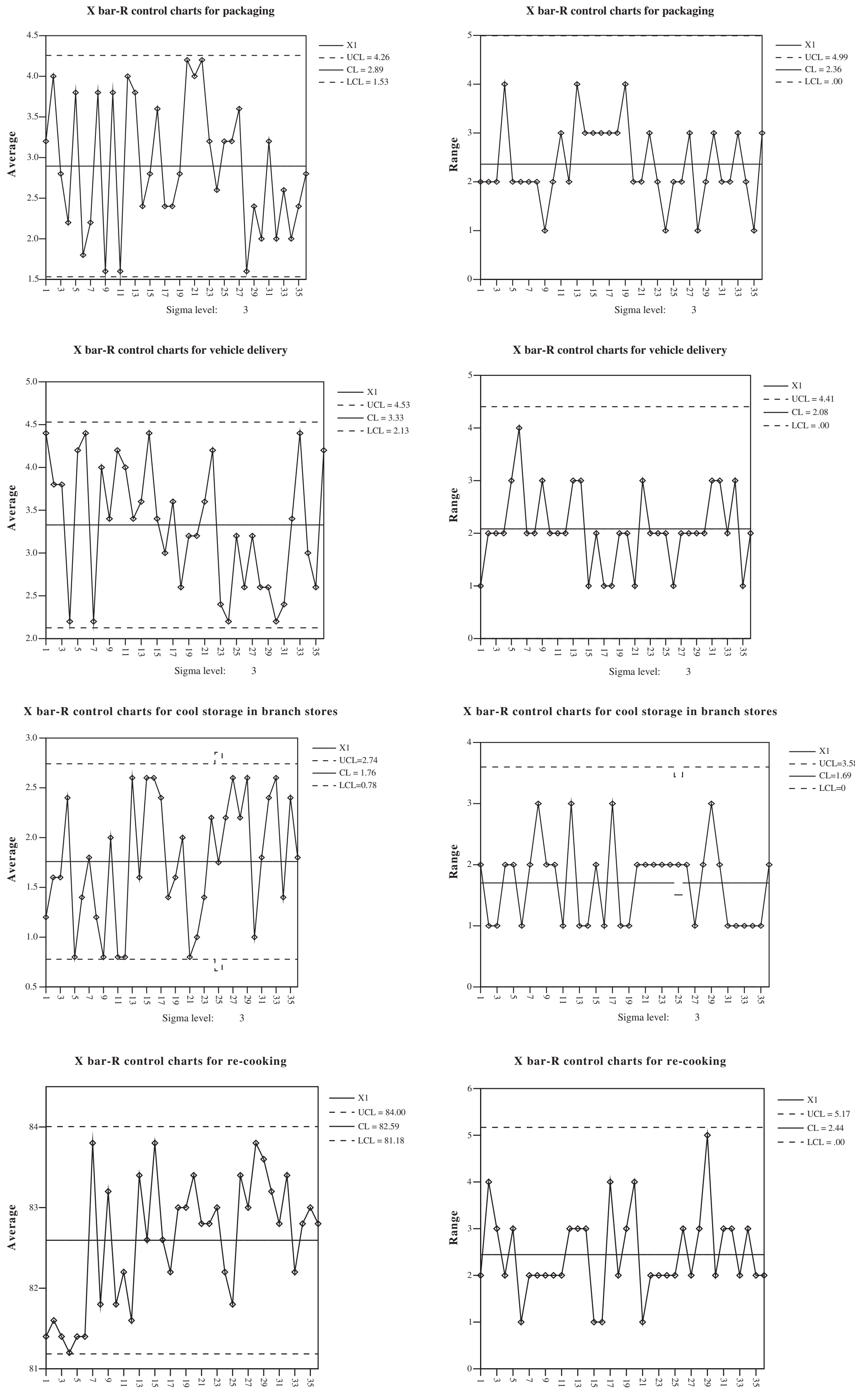

Fig. 9 (*continued*).

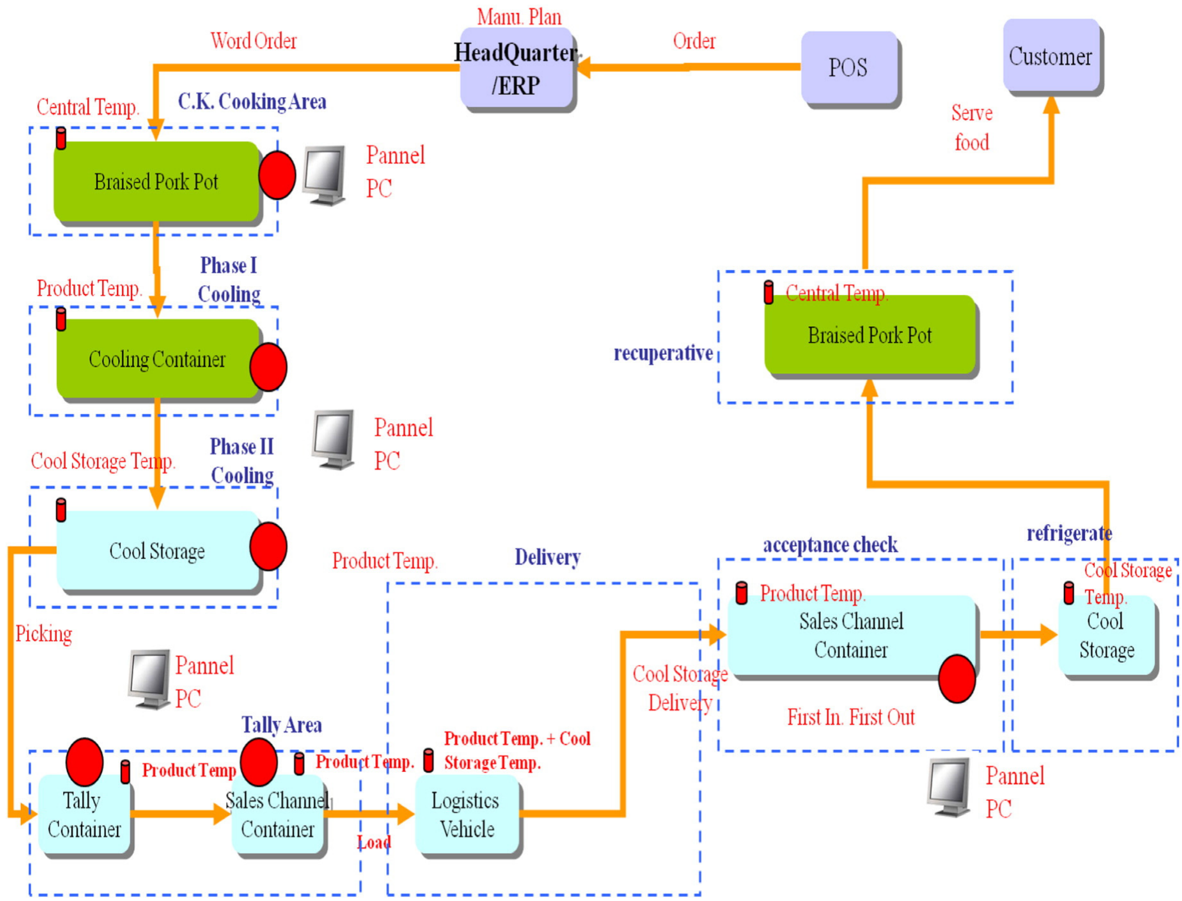

Fig. 10. CCP framework used in the production of braised pork.

braised pork. For clarity, the temperature data flow throughout the entire cold chain is illustrated in Fig. 11.

As shown in Table 3, four types of wireless sensors are adopted in this study. According to [2], a cross-logistic network and associated topology is constructed. The sensors are designed and distributed based on transmission power level, distance, linking quality into the behaviors of operators. For example, the temperature of refrigerators in the central kitchen tends to rise if staffs frequently pull out. On the contrary, the temperature of refrigerators rapidly drops down when fan and air convection continually generate cold air. Therefore, three sensors are arranged in different locations: in front of the fan, the fan that is farthest away, and near the door of refrigerators. These sensors are used to monitor refrigerators' temperature to remind responsible operators. For convenience, the sensors located in the cool-storage warehouse of central kitchens, logistic vehicles, and cool-storage cabinets of branch stores are demonstrated in Fig. 12, including their network topologies.

4. Developing new business models and conducting performance assessment

Switching from frozen to cool storage enhances product sales and boosts customer satisfaction with fresh taste. Despite the proposed system provides a number of obvious benefits; however, it was necessary to verify whether there are any adverse side effects with regard to the taste of the products. We also sought the effects of these measures on service standards, particularly with regard to attracting new customers and retaining old customers. The proposed cold chain system was shown to control temperature efficiently and preserve the quality of the dishes effectively.

4.1. New business models

The benefits of the proposed system made it possible to generate four new business models for the case company: (1) cold chain home-delivery service; (2) CVS indirect delivery; (3) CVS direct delivery; (4) flight kitchen service.

4.1.1. Model 1: cold chain home-delivery service

Most of the branches of the company in our case study are located in the vicinity of Mass Rapid Transit (MRT) stations in Taipei, Taiwan. Other branches are located approximately a 10–20 min walk from residential areas. In contemporary Taiwan, many people choose to eat in restaurants, get takeaway meals (office workers), or have food delivered (residential customers). This has given manufacturers of pre-cooked products (fully-cooked and semi-cooked) an outstanding opportunity to extend their market. Customers selecting delivery services present the greatest potential for expansion of cool-storage food products.

To make the service competitive compared to the low-temperature home-delivery service provided by 7-Eleven (pre-order service, delivery taking 3 to 7 working days to arrive at 7-Eleven store or home), this study targeted residences located near branches of the case company so that in off-peak hours, the case company could provide free home delivery in 1–2 working days for orders exceeding a minimum purchase requirement. Peak hours in branch locations are lunch time (10:30–13:30) and dinner time (17:00–20:00). Off-peak hours are 14:00–17:00. In order take advantage of off-peak hours, products held in cool storage do not require thawing. This makes them quick and easy to prepare, making it an attractive alternative for many customers. By making

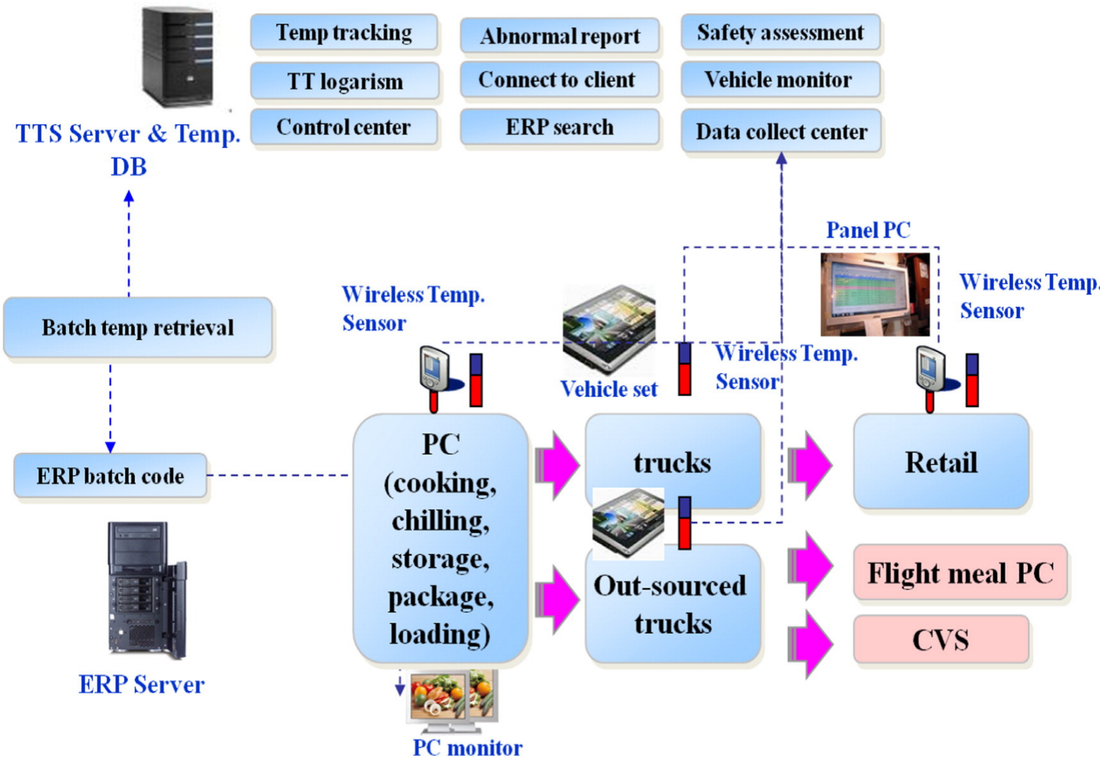

Fig. 11. Flow of temperature-related data obtained from cold chain system.

the best use of human resources during off-peak hours, we developed an innovative cool storage home-delivery service with the aim of expanding brand recognition and market penetration.

4.1.2. Model 2: CVS indirect delivery

CVS companies insist on cool storage products that do not require thawing in order to speed up service and reduce energy costs. The current trend in Taiwan is for CVS companies to adopt "CVS indirect delivery", in which the processing of fresh food is outsourced to OEM facilities. Products are delivered by the factory (using their own vehicles) to a CVS logistics center for distribution to individual outlets using CVS vehicles. For most of the products, reheating takes no more than 30–40 s in a microwave. There are many CVS channels in Taiwan, such as the Hi-Life and OK group, which owns approximately 3700 convenience stores in Taiwan. On-shelf products are easily promoted and tend to attract more buying activity. Producing CVS on-shelf products could help companies expand the scope of their business channels. Referring to Fig. 13 for the case company, this would mean the opportunity to expand business into Eastern Taiwan.

4.1.3. Model 3: CVS direct delivery

In CVS direct delivery the case company completes all food processing and packaging without outsourcing to other manufacturers. The case company has developed multi-channel cold chain services designed specifically to preserve the quality of Chinese food served in convenience stores. What cool storage products are preferred for the selected customer it may induce higher food safety risks, so that it is demanded to have more checkpoints throughout the supply chain. The food safety risk while cool storage direct delivery is seriously concerned, so that to well control the risk in the cross-logistic collaboration system is required. This provides an example of cross-logistic cold chain delivery.

As mentioned previously, the cold chain system is easily duplicated in other regions, in which all parameters remain essentially the same.

Table 3
Four types of wireless sensors employed in this study.

Name of sensors	Type of sensors	Application scope	Footnote
Portable wireless sensors	Contact	Halogen pot of C.K (Central Kitchen)	Product temperature
		Halogen pot of C.K.	Product temperature
		Steamer of C.K.	Environment temperature
Wire thermocouple sensors	Contact	Cooling Container	Product temperature
		Cooling Room of C.K.	Product temperature
		Delivery cabinet	Product temperature
Needle thermocouple sensors	Contact	Cooling Car of C.K.	Product temperature
		Halogen pot of Store	Product temperature
Environmental wireless sensors	Non-contacting	Cool storage of C.K.	Environment temperature
		Cool storage of Store	Environment temperature
		Cool storage of logistics vehicle	Environment temperature
		Steamer of branch store	Environment temperature

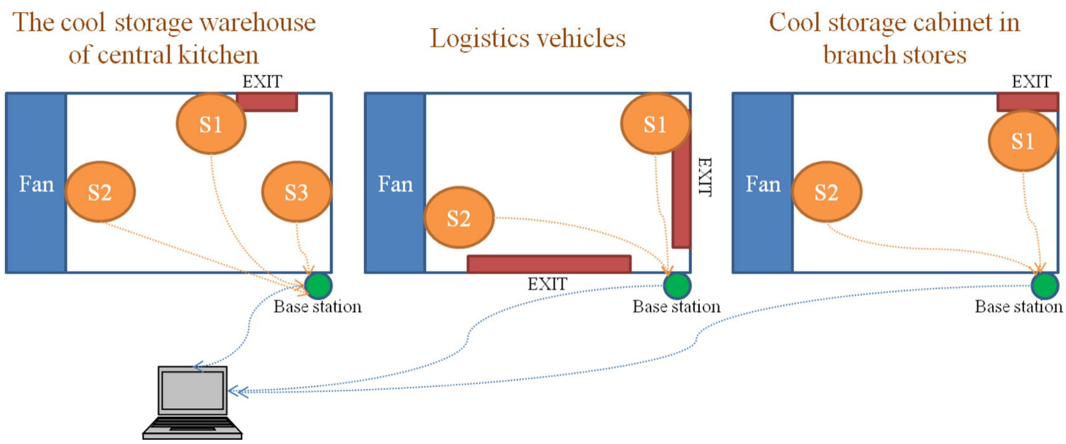

Fig. 12. Network topology designed in cold chain system.

The product selection and the packaging strategy differ from the above model. The ordering process relies on a CVS product category list; therefore, a pre-order system can be introduced. This can help to reduce inventory and decreases capital burden. In addition, this approach increases the indirect benefits of non-store, online promotion of the products resulting in a reduction in labor expenses.

4.1.4. Model 4: flight kitchen (airline catering)/airline VIP

The model of flight kitchens is similar to that of CVS indirect delivery. The major difference is lower supply volume and fewer supply spots. In this model, the case company delivers semi-manufactured food products via cool storage to international catering companies. The food is then processed and delivered to the airplane flight kitchen, where they undergo re-heating. In this case, daily delivery is required to ensure the safety and quality of all products. Referring to Fig. 14, this case company provides a selection of cool storage products such as braised pork, fried Tang-Shan pork ribs, shredded chicken and pork knuckle for China Pacific Catering Services. They also provide braised pork as an ingredient for the China Airline VIP room meal. This storage braised pork is served with high-quality rice and narazuke, resulting in a traditional Taiwanese dish. The flight kitchen business model generates less revenue than do CVS or indirect delivery; however, it promotes their vision of becoming the most prominent brand in the world for braised pork rice.

Becoming the largest producer of Chinese food in Taiwan started with the establishment of a centralized kitchen facility in 2008. The plan for “multi-channel Chinese fast food cold chain services” differed considerably from existing operations, and created multiple channels with which to pursue branch expansion and brand extension. This multi-channel cold chain business model is illustrated in Fig. 15. The ultimate goal of the company was to implement their new business model in Taiwan and then extend it to the rest of the Asian market. We had to avoid sacrificing quality for convenience in preparation, as so many fast food chains have done. We also sought to strike a balance between business expansion and preserving quality by developing a comprehensive temperature monitoring system for cold chain distribution.

4.2. Risk assessment and performance evaluation.

In order to justify the validity of the proposed framework, experimental results are demonstrated for the purpose of performance validation, including food safety assessment, food taste assessment, and performance evaluation and management.

4.2.1. Food safety assessment

As we know, temperature is a key factor affecting the activity of microorganisms in food. The activity of pathogenic microorganisms is the fastest within a range of 10–45 °C. In order to avoid food contamination

Fig. 13. DM advertising braised products in Hi-Life convenience stores.

Fig. 14. Braised pork rice in a flight kitchen of China Airlines (VIP lounge).

by toxins produced across microorganisms, the temperature must be strictly monitored and controlled in the production process. According to FDA's publication (Food and Drug Administration) in "Fish and Fishery Products Hazards and Controls Guidance" ([12]), the growth of pathogenic bacteria is proportional to food exposure time in hazardous environments (non-temperature controlled environment). For clarity, Table 4 lists three common pathogenic microorganisms and their maximum permissible cumulative time. *Bacillus cereus* is a common bacteria caused by food poisoning. The most suitable growth temperature for *B. cereus* is 30 °C which can generate toxins quickly. Within the range from 7 °C to 49 °C, the growth of *B. cereus* displays a similar characteristic in food-storage equipment of the cold chain. Thus, without loss of generality, this study investigates risk assessment on *B. cereus* in food safety.

Table 4
The guidance for controlling pathogen growth and toxin formation in fish and fishery products.

Potentially hazardous condition	Product temperature	Maximum cumulative exposure time
Growth and toxin formation by *Bacillus cereus*	39.2–43 °F(4–6 °C)	5 days
	44–59 °F(7–15 °C)	1 day
	60–70 °F(16–21 °C)	6 h
	Above 70 °F(21 °C)	3 h
Growth of *Listeria monocytogenes*	31.3–41 °F(−0.4–5 °C)	7 days
	42–50 °F(6 ~ 10 °C)	1 day
	51–70 °F(11–21 °C)	7 h
	71–86 °F(22–30 °C)	3 h
	Above 86 °F(30 °C)	1 h
Growth and toxin formation by *Staphylococcus aureus*	50 °F(10 °C)	14 days
	51–70 °F(11–21 °C)	12 h
	Above 70 °F(21 °C)	3 h

Referring to Table 2 again, it provides toxin formation risk of *B. cereus* measured in terms of food safety coefficients decrease per minute with regard to various ranges of temperature:

- 4–6 °C: $1/(5*24*60) = 1/7200$ per min loss of safety quality.
- 7–15 °C: $5/(5*24*60) = 1/1440$ per min loss of safety quality.
- 15–21 °C: $20/(5*24*60) = 1/360$ per min loss of safety quality.
- >21 °C: $40/(5*24*60) = 1/180$ per min loss of safety quality.

Apparently, when the food is treated by unsuitable storage in a longer time, or the higher temperature in the storage environment, the risks in

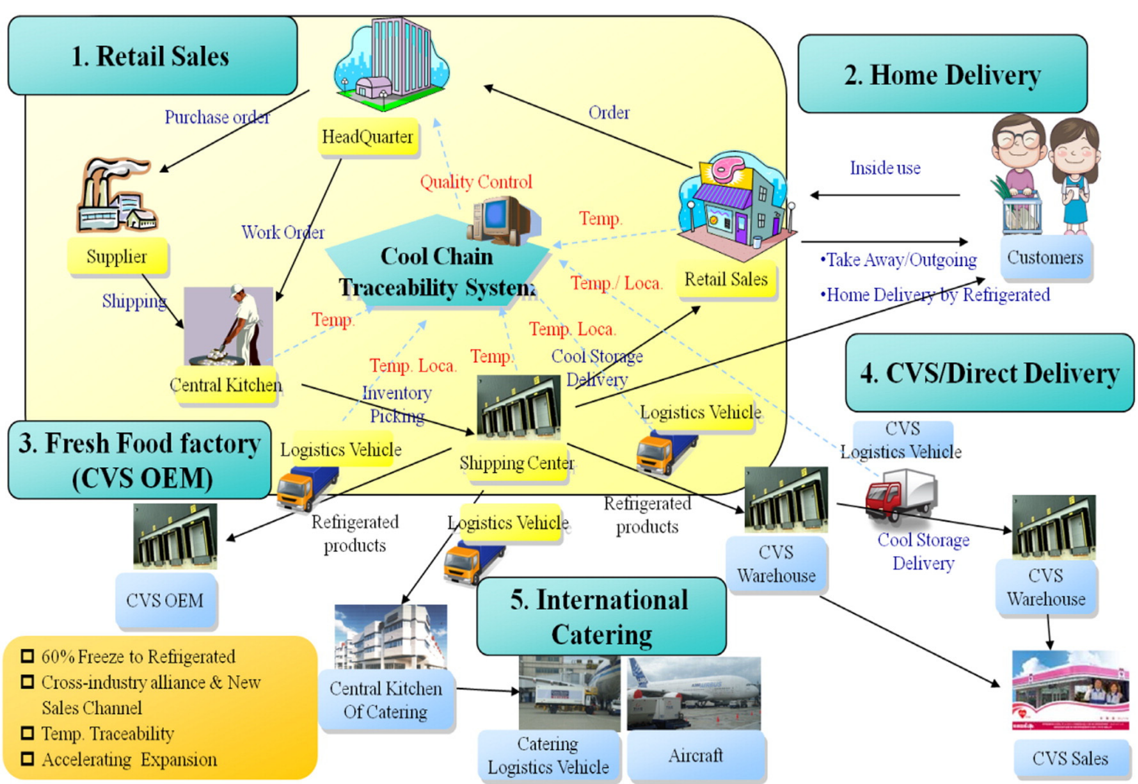

Fig. 15. An innovative multi-channel business model for cold chain management.

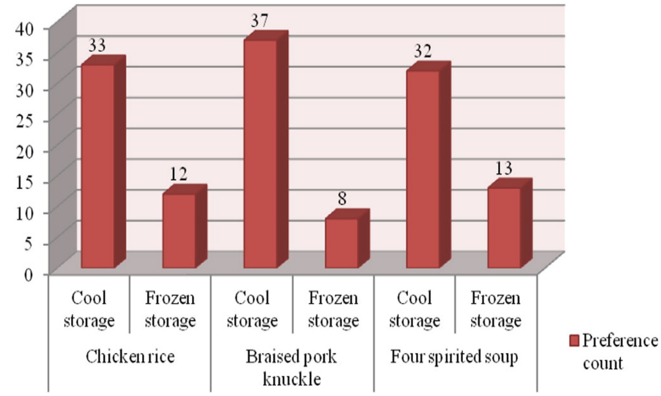

Fig. 16. Experimental results of food tasting experience activity.

food security significantly increase. The maximum value of food-security risk is unity if more than one pathogen has been detected per minute. Therefore, when the products have switched from frozen storage to cool storage, the constraints in food's storage time still exist in practice.

4.2.2. Food taste assessment

In order to justify whether food tastes are perceived more delicious in cool storage than in frozen storage, this study conducted an experiment in food tasting experience. During the activity, we prepared one hundred bowels of chicken rice, braised pork knuckle, and four spirited soup. Besides, 45 volunteers were recruited in participation. The whole process is briefly described as follows: the invited participants taste foods individually and separately: foods are cooked in cool/frozen storage without revealing the premise of the storage environment (participants are unknown about either cool storage or frozen storage). As illustrated in Fig. 16, the results in the activity showed that more than two-thirds of the participants vote the food cooked under cool storage better than the food cooked under frozen storage.

4.2.3. Performance evaluation and management

This study constructed a cold chain system for multi-channel Chinese food restaurants covering a centralized kitchen and transportation to branch stores. The integration of cross-logistic cold chain systems is one of the most significant achievements of this study. In collaboration with a CVS logistics group, the proposed temperature-monitoring system ensures a minimization of missing or incomplete data of food temperature during long-distance delivery. Another major achievement is the introduction of a branch-wide cold chain system, which includes a freezing/thawing system, a high-efficiency cool storage delivery system, and a cool storage system for branch stores. We created and integrated an end-to-end (central kitchens to branch stores) system, which successfully sets a good template for the food industry.

In running four new business models, sixteen products were selected and shifted from frozen storage to cool storage. In Table 5, we analyzed four business models as well as their product strategies. In addition, the economic feasibility of these models are measured and analyzed in Table 6. In this case, the use of information communication technology in conjunction with the IoT based cold chain system enabled the company to preserve food quality and develop new models capable of expanding wider range of food services, such as extending products to an airline catering service and VIP rooms, selling new products into thousands of convenience stores, and creating a new home delivery service. Meanwhile, yearly energy cost of cooling has been reduced about 10% while annual sale of braised pork rice has been enhanced by 36% (from 4.44 million bowls in 2009 to over 6 million bowls in 2010). Obviously, the proposed system significantly benefits the case company in various perspectives as well as its brand image.

5. Conclusions

Today, many studies have been published to address temperature monitoring of the cold chain for environmentally sensitive goods. The emphasis on this issue stems from the critical role of temperature because it has great impacts on the social, economic, and environmental performance of food supply chain. Different from the previous studies, this paper proposes a cold chain system for a multi-channel Chinese food processing system, including preparation in a centralized kitchen and transportation to branch stores. The whole system includes several sub-systems, such as a freezing/thawing module, a cool-storage delivery module, and a cooling-storage management module in branch stores. After the proposed system was successfully applied to the VIP room of China Airline and other 6 airlines, the proposed cold chain system also helped the case company receive orders of cool storage products from China Pacific Catering Services and more than 1000 Hi-Life convenience stores. In particular, for improving quality control of cold chain systems, this study proposes an quantitative framework which combines a wireless sensor network with CCP criteria based on $\overline{X}$–R control charts.

Table 5
Product supply strategy under multiple cold chain service models.

	Product/Mode	Sales channel	Home delivery	Fresh food factory (CVS OEM)	Convenience store	International catering
Cool storage products before develop cold chain system	Meat Soup Sauce Other	Braised pork, Four spirits soup, Bitter gourd and pork rib soup, etc.	None	Braised pork, Braised shredded bamboo shoots, etc.	Customized products (braised products, etc.)	Braised pork, Narazuke, etc.
Cool storage products after develop cold chain system	Meat	Braised pork hock, Braised pork knuckle, Braised pork tendon, Shredded bamboo shoots, Shredded Chicken, etc. (5 items added)	Festival gift box	Braised pork, knuckle	Customized Product, such as braised products, etc. (2 items added)	Braised pork, Braised tendon, Braised pork hock, Tangshan pork ribs, Shredded chicken, etc. (1 item added)
	Soup	Dragon marrow soup, Corn soup, Daylily pork rib soup, Chinese clear soup, etc. (4 items added)	Festival gift box (1 item added)		Custom Product (1 item added)	
	Sauce	Soybean oil sauce, chicken oil sauce, etc. (2 items added)				
	Other		Festival gift			

Table 6
Analysis of economic feasibility for the presented business models.

	Fresh food factory (CVS OEM)	Convenience store (CVS)	Home delivery	International catering
Product	Braised pork rice meal box, Braised pork knuckle meal box, etc.	Braised pork, Braised meat products, Festival gift box, Soup, etc.	Festival gift box, Soup gift box, Braided pork gifts, Braised product, etc.	Braised pork, Quality rice, Pickled cucumbers, etc.
Scope	All 1200 Hi-Life CVS channel in Taiwan	All the 1000 OK-MART CVS channel in Taiwan	Customers around all the sales channels	China Airline VIP Room, Aircraft
Product appeal	Convenient, Delicious, Fair Price	Delicious, Gifts	Convenient, Delicious, Fresh	Delicious, Higher Price, Traditional Food Culture
Product price	US$1.75	US$12.67–19.02	US$9.5–19.02	US$0.8–1.6
Quality control	Multi-temperature layered delivery	Multi-temperature layered delivery	Single-temperature zone delivery	Multi-temperature layered delivery
Business effect	Expansion Business Scope, and Brand Increase Revenue	Expansion Business Scope, and Brand Increase Revenue	Expansion Business Scope, and Brand Increase Revenue	Expansion Business Scope, and Brand Increase Revenue
Cost	Cost of ingredients, Cooking, Delivery	Cost of ingredients, Cooking, Delivery	Delivery Cost	Cost of ingredients, Cooking, Delivery

In summary, it contributes to both academic researchers and industrial practitioners by demonstrating the following merits:

- *In an economic context, enhancing product sales: introduction of the new system increases annual sales of braised pork rice from 4.44 million bowls to over 6 million bowls within a year.*
- *In a social context, creating job opportunities: it also produced 150 job opportunities, with extra revenue of more than US$6.35 million, and a 10% reduction in energy costs.*
- *In an environmental context, reducing energy consumption: the consumption of electrical power in the central kitchen was reduced, to contribute turnover from US$14.23 raised to US$18.64 per kilowatt hour. Likewise, it was also used in stores to contribute turnover from US$4.32 raised to US$4.58 per kilowatt hour.*

In the near future, the case company will continue to expand the ratio of cool storage products to all products expected to increase from 50% to 75%. Eventually, the case company wishes to invite its upstream suppliers to involve a wider coverage via supply chain collaboration and so to make other new channels to join as well. In future studies, fusing big data mining with the architecture of IoT (internet of things) in food industries deserves to be further explored.

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