Computer Standards & Interfaces 45 (2016) 62–78

Contents lists available at ScienceDirect

Computer Standards & Interfaces

journal homepage: www.elsevier.com/locate/csi

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

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ARTICLE INFO

Article history:
Received 2 April 2015
Received in revised form 12 December 2015
Accepted 17 December 2015
Available online 23 December 2015

Keywords:
Cold chain
Control charts
Internet of Things
Time–temperature indicator
Wireless sensors

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.

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

http://dx.doi.org/10.1016/j.csi.2015.12.004
0920-5489/

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