Review

Distribution planning for perishable foods in cold chains with quality concerns: Formulation and solution procedure

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ABSTRACT

Background: Food safety and quality management is attracting more and more attention. Fresh foods are characterized by their perishable and temperature-sensitive nature. Thus, there is a need for cold chain management. In order to ensure delivery of safe, fresh, high-quality foods to customers, strict time and temperature control are special requirements which must be incorporated during distribution planning.
Scope and approach: This study modeled a cold chain food distribution planning problem, aiming to generate a distribution plan for fulfilling customer requirements for various foods with pre-appointed quality levels at the lowest distribution cost. The quality level was defined based on the estimated shelf life, which varies by food type and storage temperature, and is characterized by a stepped decrease as time goes on. Upward substitution of quality levels is implemented in the shipment of customer orders to ensure customers receiving the foods with ordered quality levels. The optimization of temperature setting for food storage in multi-item-multi-temperature vehicles was also involved in distribution planning. To solve the problem, an algorithm based on adapting Biogeography-based Optimization (BBO) was developed. The genetic algorithm was employed as a benchmarking method. Two designed examples regarding chilled meat distribution are illustrated.
Key findings and conclusions: The results indicate that the generated distribution plan can ensure the fulfillment of customer requirements for various foods and food quality levels at the lowest cost. The superiority of the proposed adaptive BBO in both the solution quality and stability was also demonstrated.

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1. Introduction

Food safety is a major issue in the food system. In particular, the development of the food processing industry and specialized division of the food supply chain have resulted in food safety and quality management attracting more and more attention. Concurrently, food-safety-related laws and regulations have undergone various developments to protect the safety and health of consumers. This shifts the existing safety and quality focuses from a reactive to a preventive approach (Grover, Chopra, & Mosher, 2016). Fresh foods require advanced approaches to the supply chain management because of their high perishability. The difficulty in preserving such food products in supply chains presents a direct problem, where the perishability is required to be handled in ways not necessarily conducive to the traditional view of ambient temperature activities. As indicated by Hertog, Uysal, McCarthy, Verlinden, and Nicolaï (2014), temperature has been taken as the primary concern for maintaining the quality in the supply chain of perishables. Many efforts have been shown for enhancing the supply chain management of perishable food products (e.g. Aiello, La Scalia, & Micale, 2012; Amorim & Almada-Lobo, 2014; Bruckner, Albrecht, Petersen, & Kreyenschmidt, 2013; Chang, Zhu, & Lin, 2015; Chen, Hsueh, & Chang, 2009; Defraeye et al., 2015; Giménez, Ares, & Ares, 2012; Kuo & Chen, 2010; Rong, Akkerman, & Grunow, 2011; Zou & Xie, 2013).

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Recently, due to the advancement of information and communication technology, more environmental data can be monitored and collected to help enterprises with the improvement of supply chain management of perishable food products. To optimize the perishable food supply chain management, Hertog et al. (2014) applied the generic shelf life model for first-expired-first-out warehouse management, in which sensors were used to collect more data of conditions (e.g., O_2, CO_2 and relative humidity) since they also have an impact on the shelf life. La Scalia, Settanni, Corona, Nasca, and Micale (2016) developed a supply chain monitoring system based on a prototype system, namely Smart Logistics Unit (SLU), to real time monitor the parameters of food supply chain to dynamically determine the residual shelf life of perishable food products. In their simulation experiments, different transportation conditions in terms of time of vibration were taken into account. Sciortino, Micale, Enea, and La Scalia (2016) further applied the prototype of SLU with GPS module for positioning the truck in a real-time manner, and the captured data were transmitted to the webGIS platform for predicting shelf life variation during product transportation.

The deterioration of fresh foods generally is caused by physical, chemical and biological changes that occur throughout the supply chain, diminishing the shelf life (Giménez et al., 2012). Also, the low thermal inertia of fresh foods makes the foods themselves more vulnerable in the supply chain. It is known that maintaining proper low storage temperature throughout the supply chain helps slow down the quality deterioration and thus extend the shelf life of fresh foods. Correspondingly, time and temperature control becomes a critical issue in the food supply chain, driving demand for cold chain management (Aiello et al., 2012; Defraeye et al., 2015; Laguerre, Hoang, & Flick, 2013; Montanari, 2008; Reed, 2005).

Distribution planning is one of the major activities in cold chain management. Compared to ambient temperature distribution, in addition to the extra investment in fleets of temperature-controlled vehicles, more strict temperature and time control is required to maintain food quality in cold chain distribution. However, this significantly increase the distribution cost (Hsu, Hung, & Li, 2007). Furthermore, serving consumers within allowable delivery time windows and simultaneously meeting their expectation of food quality can increase the complexity of cold chain distribution planning (Chen et al., 2009).

There has been little research on distribution planning adapted to cold chain applications. Overall, two main directions have been observed from the existing research. One is that efforts have been made to consider the cost and impact of food quality deterioration in the planning models (Amorim & Almada-Lobo, 2014; Chang et al., 2015; Chen et al., 2009; Hsu et al., 2007; Osvald & Stirn, 2008; Trihardani, Rusdiansyah, & Vanany, 2011; Zhang & Chen, 2014; Zou & Xie, 2013). The other is that multi-item-multi-temperature vehicle distribution has drawn attention (Cho & Hsu, 2008; Hsu & Chen, 2014; Hsu & Liu, 2011; Trihardani et al., 2011; Zhang & Chen, 2014). Few studies except those conducted by Trihardani et al. (2011) and Zhang and Chen (2014) have addressed the issues which simultaneously involve these two directions.

Under the consideration of food quality deterioration, these studies mainly focused on modeling the quality decay with varying time or temperature to reflect the quality loss and aimed to derive a distribution plan with minimum overall cost. However, meeting customer requirements for appropriate food quality has not been considered yet. In practice, for specific usage, a customer may request fresh foods which are still fresh but with a shorter remaining shelf life in order to get a price break or to use for specific purposes. And customers are willing to accept the foods with

higher quality level for compensating for the deficiency of what they ordered; this results in added cost for distribution operators. This will complicate the distribution planning problem and has not been considered in the literature.

For the multi-item-multi-temperature vehicle distribution, the multi-temperature joint distribution approach (Kuo & Chen, 2010), in which each vehicle can distribute food of varying temperature has been most commonly considered. Generally, multiple storage spaces with different temperature ranges are arranged in a vehicle, either by dividing a single vehicle compartment into multiple temperature zones, or utilizing boxes and cabinets with cold accumulators in a regular vehicle. The temperature ranges are roughly categorized into, for example, frozen, refrigerated, and regular, instead of determined by explicit temperature values. Food products are simply assigned to a feasible but not optimal space according to their suitable storage temperature ranges. However, considering the different deterioration properties of perishable and temperature-sensitive foods and the different quality requirements from customers, the optimal setting of storage temperature for each category of foods in a vehicle during distribution process is needed. This has been rarely addressed in the previous studies.

In this study, we modeled and resolved the problem of cold chain distribution planning, which aims to satisfy customer requirements for preferred food quality levels within a specific service time window at the lowest cold chain distribution cost. The quality level of foods was defined based on the estimated shelf life. The shelf life varies by product type and storage temperature, and is characterized by a stepped decrease as time goes on. Quality substitution cost will arise if higher quality levels than that customer ordered are shipped for offsetting the continuous deterioration of food quality during distribution routing. Besides, customers are willing to accept the foods of higher quality levels at the price of what they ordered when the foods of their ordered quality levels run out; however, this raises the cost and may result in the shortage of foods of higher quality levels. Moreover, the storage temperature set for different storage spaces of a multi-item-multi-temperature vehicle was also considered in this problem. The storage temperature setting directly contributes to the variable costs of the cold chain distribution problem, and affects the speed of deterioration in food quality level during vehicle routing.

To solve this cold chain distribution planning problem, a relatively new metaheuristic algorithm, biogeography-based optimization (BBO) (Simon, 2008), which belongs to the class of evolutionary algorithms (EA), was adapted. BBO has been applied to various problems and has provided satisfactory results (e.g. Berghida & Boukra, 2015; Garg & Deep, 2015; Hadidi, 2015; Simon, Rarick, Ergezer, & Du, 2011; Zheng, Ling, Shi, Chen, & Chen, 2014). However, few applications of BBO have aimed to solve the distribution planning-related problems, except that by Berghida and Boukra (2015) which applied Solomon benchmark instances (Solomon, 1987) to demonstrate the satisfactory ability of BBO to solve the vehicle routing problems. The genetic algorithm (GA) which also belongs to the evolutionary category is the most commonly used metaheuristic algorithm for optimization. The GA has shown convincing ability to solve the distribution planning-related problems (e.g. Anujuprana, 2015; Baker & Ayechew, 2003; Hwang, 2002; Tasan & Gen, 2012). In this study, the GA was applied to be a benchmark problem solving algorithm.

2. Problem formulation

Our focused cold chain distribution planning problem is formulated as a mathematical program. Specifically, chilled meat, a