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Chilled or frozen? Decision strategies for sustainable food supply chains

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ABSTRACT

Along the food supply chains (FSC), energy plays a strategic role, being fundamental to guarantee quality and influential in the determination of economic values. Moreover, the same type of product may flow through chains differing in energy requirement, processing equipment and time spent in the chain itself.

These differences between the FSCs (short vs. longer product lives and storage times, fast vs. slower transportation, low vs. higher energy contribution) motivated the study, which aims at capturing in an analytical model the relationships between the relevant parameters influencing the problem, thus addressing a possible approach to the chain optimisation.

By the modelling approach proposed, jointly looking at economic aspects and energy efforts required to condition and preserve the product quality over time, it is possible to address new considerations for understanding FSCs peculiarities, so as to support decisions and improving the sustainability of the solution adopted.

1. Introduction

There are several and different ways for treating and preserving food: however, the greatest part of them requires some contribution of energy. For example, heating was used since the oldest times, because of warm sources availability, while producing cold temperatures, excluding determined geographical areas, has acquired more relevance in the recent times, thanks to energy availability (refrigerators) and, in the years preceding, ice transportability. Nowadays, several supply chains for foods are based on chilled and frozen goods: different transport chains and their technical features are described in James et al. (2006). It is evident that a key element within these chains is energy, also in its different forms, as it is a necessary source to guarantee quality-based processes. Furthermore, the use of energy implies the consumption of resources (frequently, non-renewable ones) and this fact directly influences the sustainability of the FSC considered, together with its economic performance.

Distribution and storage of frozen food fall into the category of "cold chains", in which the products are kept at low temperature so as to preserve their quality. In "cold chains" energy should be appropriately used to prevent food products deterioration over time, avoiding their value decrease (e.g., due to spoilage of perishable products) and guaranteeing quality preservation.

Food quality and the nutritional value of food itself could be related to some important nutrients characteristics (e.g., vitamin C level for several vegetables, sugar level for several fruits, proteins for meat, etc.), which begin to deteriorate immediately upon harvest or butchery: the aim of cold chains is both to preserve quality and to limit the loss in value over the following stages of the chain from the field to the consumer.

The present paper aims at investigating the role of energy in a FSC where a producer collects the products, freezing them to the temperature set for their preservation, and transports the products to an intermediate distributor for cold stocking before final delivery to retailers. The temperature level must be guaranteed throughout the chain, from the producer to the retailer and frozen products face a cold storage the duration of which determines the level of energy demand. Moreover, the lower the temperature, the higher the energy required and the longer the product life: i.e., the optimisation of the FSC outlined requires the modelling of the chain itself, taking into consideration the temperature set and its impact on quality (i.e., food preservation, together with its nutritional values), energy and associated costs.

The aim is to present a model for FSC configuration encompassing the influence of both temperature and storage time, thus appreciating their impact on product quality, costs and sustainability of the chain, as related to quality degradation and energy consumption.

To this end, the paper will be organised as follows. Section 2 offers a broader view of FSC, so as to set the problem dealt within an appropriate background. Section 3 gives the notation and the framework for the proposed modelling approach. Section 4 is

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devoted to the comments to the model and to some insights offered by the model itself. Finally some concluding remarks jointly and foreseeable developments are given in Section 5.

2. Literature background

FSCs present peculiar features with respect to other goods chains and, also from this point of view, FSCs reveal challenging aspects for inventory and production researchers (Zavanella and Zanoni, 2009). For example, FSCs are affected by peculiarities close to typical production issues, but worthy of investigation (e.g., Akkerman and van Donk, 2007):

- frequently, setup times are sequence dependent (think about cleaning, equipment regulation and selection of packages) both in time and costs;
- the time of storing should be limited, not only because of limited shelf life, but also because of the need for dedicated equipment and space, which could be additionally limited when product mixing is to be avoided; and
- processing should be fast, by means of traced and high-quality systems.

However, food processing and distribution may refer to significantly different types of chains: this fact may be easily perceived when comparing the supply chain of fresh foods (characterised by short product lives, fast transportation and low energy contribution, mainly concentrated in the transport phases rather than in stocking) and the frozen foods one (long product lives, slower transportation, high energy contribution, especially at the stocking phases). The short description given spotlights the different role played by energy in these two chains, both in the form of energy (e.g., fuel and electricity) and time intervals of energy usage (e.g., food stocking time before final consumption). Of course, mixed situations may also be found in practise, such as freezing–defrosting–cooking–freezing or fresh delivery-freezing.

Moreover, in the recent years, the need for an accurate chain control and its monitoring has emerged as one of the most critical issues (Montanari, 2008). The need for guaranteeing food safety and quality is directly linked to physical, biological and chemical parameters, which frequently interact with each other, as in the case of temperature and moisture. From this point of view, regulations are also playing a remarkable role in boosting the application of new technologies and tailored managerial approaches to FSCs (Bogataj et al., 2005).

Within the scenario described, classic inventory models could be implemented with appropriate adjustments (e.g., perishable and variable holding costs) as well as new managerial practices could be investigated and successfully applied. To this end, efforts have been produced by researchers, addressing the critical aspects and the relevant parameters of the problem. For example, Zhang et al. (2003) present an algorithm to optimise the structure of cold chains minimising storage and transportation costs (considering product quality concerns). Zanoni and Zavanella (2007) consider the shipping of a set of different perishable products from a vendor to a buyer with the objective of minimising the sum of the inventory and transportation costs. Kuo and Chen (2010) propose specific chain architecture for perishable goods, based on multi-temperature distribution centres, while Cai et al. (2010) discuss the issues of coordination between the producer and the distributor in fresh food chains. van der Vorst et al. (2009) present a simulation tool for the design of food chains, jointly taking into account food quality change and environmental load of the different scenarios evaluated, considering different inherent uncertainties, too. An updated review of planning models in the agri-food supply chain is offered in Ahumada and Villalobos (2009), thus confirming the great attention gained by the argument and the different approaches to it. Recently, Akkerman et al. (2010) presented a comprehensive review of the quantitative operations management research on food distribution management: they discussed the state-of-the-art and identified challenges for further research.

Finally, despite of their importance, distribution centres for fruit and vegetables have received limited attention in the performance management literature (Manikas and Terry, 2010).

The present contribution aims at studying the optimal replenishment quantities along the chain, so as to meet efficiently the market demand at the retailers, but taking into consideration the energy effort at the production site (due to the proper processing of the products), the additional energy effort along the distribution channel (as required to preserve the quality of the product themselves) and the impact determined by the cost of product deterioration.

3. Problem definition and notation

The system studied consists of a distributor that procures and stocks chilled or frozen products from a producer (who properly treated the products, e.g., freezing them) and transports them to different retailers, thus reaching a final target market for sale (Fig. 1).

The model proposed will try to capture the link between the quality degradation rate of the food and the energy effort required for its preservation. From this point of view, the most relevant parameter linking quality and energy is the temperature set to preserve food: the lower the temperature, the higher the energy required along the chain and the longer the food quality preservation.

3.1. Quality change

Even when the optimal temperature of the products is maintained throughout the cold chain, the quality of the products decreases over time (Zhang et al., 2003). In general, quality degradation of food products depends on the storage time t, the storage temperature T, and additional parameters depending on the storage atmosphere. More generally, quality degradation may be described by the following equation (for more details see Labuza, 1982):

$$\frac{dq}{dt} = kq^n, \quad (1)$$

where q is the quality of a product, k the rate of degradation (depending on environmental conditions) and n is a power factor defined as the order of the reaction, determining how the reaction rate is dependent on the amount of quality q remaining. Temperature plays a primary role in product quality degradation: the

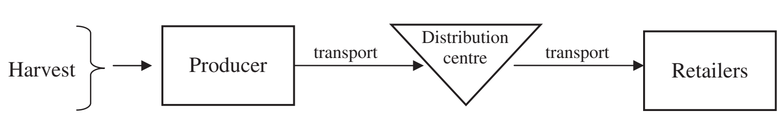

Fig. 1. The considered chilled-frozen food supply chain.