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Joint optimization of production, transportation and pricing policies of complementary products in a supply chain

Navid Dehghanbaghi, Mohsen S. Sajadieh *

Department of Industrial Engineering & Management Systems, Amirkabir University of Technology, 15875-4413 Tehran, Iran

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ABSTRACT

In this paper, we consider the joint optimization of production, inventory, transportation and pricing policies in a multi-product two-stage supply chain. The products are complementary and their demands are not only dependent on their own price but also on their complementary product price. Mathematical model of the problem is presented in both centralized and decentralized supply chains. Exact algorithms are presented using mathematical and convexity analysis to solve mixed integer nonlinear models. Numerical studies show that the profit of centralized supply chain is more stable compared to decentralized supply chain when the dependency rate of products changes.

1. Introduction

As presenting products with lower prices is getting more important in nowadays competitive environment, companies not only tries to reduce their own cost but also corporate with their supply chain (SC) to reduce total system cost. In this regard, decisions in SCs can be made into two categories, i.e. centralized and decentralized. In centralized supply chains (CSC), decisions are made according to the benefits of whole SC and the members have complete access to the whole information of each other. However, in the decentralized supply chains (DSC), each member has only access to its own information and tries to maximize its own profit regardless of other members. Joint Economic Lot Sizing (JELS) problems known as integrated vendor-buyer problems try to optimize joint total cost/profit of all members, simultaneously.

JELS problem was first introduced by Goyal (1977) with a single vendor and a single buyer. It was assumed that the production rate is unbounded and the transportation policy between vendor and buyer is lot-for-lot. Banerjee (1986) later released the assumption of infinite production rate. Lu (1995) developed a model under the assumption that non-delayed equal-sized shipments policy is used for delivery which means shipments can be shipped while orders are producing.

Goyal (1995) studied a model in which the shipment size increases geometrically. Hill (1997) developed the Goyal's (1995) model where the geometric growth rate in shipments size is a decision variable. Goyal and Nebebe (2000) presented geometric-then-equal-shipments policy for the first time. In this policy, the size of shipments is small at first and then its size growths by multiplying a factor and finally the shipment size will be constant for some shipments. Hill (1999) studied a problem where there is no predefined assumption on the shipment delivery policy. He showed that the optimal shipment delivery policy is geometric-then-equal-shipments policy.

The JELS literature has been extended in several directions. It can be divided into different categories such as stochastic lead time (e.g., Sajadieh, Jokar, & Modarres, 2009), Just-in-time manufacturing (Kim & Ha, 2003), three–level SCs (e.g., Sajadieh, Fallahnezhad, & Khosravi, 2013), and dual sourcing (e.g. Sajadieh & Thorstenson, 2014). We refer to Ben-Daya, Darwish, and Ertogral (2008) and Glock (2012) for comprehensive reviews of the JELS literature.

Most papers in the literature studied single product problems which makes models less applicable. Lu (1995) developed single-vendor, multi-buyer model by considering multiple product types where each buyer demands a specify product type. Kim, Hong, and Chang (2006) considered a multi-product types JELS problem in a three level SC comprising a single supplier, one manufacturer and multiple retailers. It was assumed that all products are produced from the same raw materials. Similarly, Pal, Sana, and Chaudhuri (2012) studied a three level SC where there are multiple suppliers, single manufacturer and multiple retailers. It was assumed that each supplier supplies one type of raw material and manufacturer produces several product types by combining

* Corresponding author.
E-mail address: sajadieh@aut.ac.ir (M.S. Sajadieh).

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certain percentages of different raw material types according to the demand of customers for each final product.

On the other hand, some papers in the literature studied the cases in which the demand depends on factors such as time, price, inventory, trade credit, tax, etc.

Chang, Ho, Ouyang, and Su (2009) studied a two level SC where the demand is sensitive to the product price at retailer. Sajadieh and Jokar (2009) considered a problem in which the demand is price-sensitive. They concluded that in the case of high dependency of demand to price, high purchasing price between vendor and buyer can result huge improvement through coordination of buyer and vendor. Sarakhsi, Ghomi, and Karimi (2016) introduced a new hybrid algorithm for JELS problem assuming the demand is price sensitive. Zanoni, Mazzoldi, Zavanella, and Jaber (2014) considered a linear demand function dependent on the price and its environmental performance. The model optimizes the product price.

Chung (2012) and Lin, Ouyang, and Dang (2012) considered trade-credit dependent demand. Moreover, there are some situations when the demand is sensitive to the time for the products which have a limited life cycle. Omar (2009) and Yang, Wee, and Hsu (2008) studied the problems that the demand decreases over the time.

It is also possible that the demand depends on the amount of displayed products such as groceries, super markets etc. Sajadieh, Thorstenson, and Jokar (2010) took into consideration a stock-dependent demand for two-stage SC with a single vendor and a single buyer. They showed that the coordination is more beneficial when demand is more dependent upon displayed stock.

As can be seen, most papers in literature have studied an integrated production-inventory with a single product type. There are few papers which have considered multi-product types problems. However, these papers assumed that the demand of each product type is independent from other products. However, most SCs in real world are multi-product types and the demand of each product types depends upon the demand and price of other types. One of the important factors affecting the demand of a product is its complementary or substitute product prices. So ignoring the correlation between substitute or complementary products may result in unrealistic conclusions. This is more important when we see that most of the SCs present a portfolio of complementary and/or substitute products.

In this paper, we study a price-dependent demand production-inventory problem. It is assumed that two types of complementary products are produced, i.e. the demand of products depends not only on its own price but also on the price of its complementary product. Generally, the innovations of presented paper can be summarized as follows:

- A two-stage SC with a single vendor and a single buyer is considered in which two types of complementary products are produced.
- The demand of product types depends not only on its own price but also on the price of its complementary product.
- Production, shipment, inventory and pricing policies are jointly optimized in CSC and DSC. Moreover, the impact of SC coordination is studied.

The rest of paper is organized as follows: In Section 2, proposed problem is defined, and notation and assumptions are presented. Mathematical models of CSC and DSC as well as the solution approaches are presented in Section 3 and Section 4, respectively. Numerical results and sensitivity analysis are presented in Section 5. Conclusions and further research directions are summarized in Section 6.

2. Problem definition and notation

Consider a two stage SC including a vendor and a buyer. The vendor produces two products that are complementary. As soon as the on-hand inventory at the buyer drops to the reorder point, an order is released by buyer. Fig. 1 shows the net stock of vendor and buyer. As can be seen, the vendor produces two complementary products at different rates in a single production line and fulfills the orders of the buyer during and after each production period.

The following notations are adopted:

P_i	The vendor production rate of product i
A_{v_i}	Vendor's setup cost for product i
A_{b_i}	Buyer's ordering cost for product i
h_{v_i}	Inventory holding cost at the vendor per year for product i
h_{b_i}	Inventory holding cost at the buyer per year for product i
C_i	The buyer unit purchasing price (charged by the vendor) for product i
α_i	The potential demand for product i (as its price and its complementary product price are zero)
β_i	The slope of the demand function of the product i to its own price
λ	The slope of the demand function of the product i to its complementary product price
Decision variables	
δ_i	The selling price of product i
Q_i	Buyer's order quantity per period for product i
n_i	Number of shipments delivered to buyer by vendor per production period for product i

The following assumptions are used throughout this paper:

1. The demand of products depends not only on its own price but also on its complementary product. Therefore, the demand function of each product type is as below (see e.g., Yan & Bandyopadhyay, 2011, and Lus & Muriel, 2009):

$$D_i = \alpha_i - \beta_i\delta_i - \lambda\delta_j \quad i,j = 1,2; i \neq j \tag{1}$$

As can be seen in Eq. (1), there is an inverse relationship between the demand of product type i (D_i) and its price (δ_i) as well as its complementary product price (δ_j). The demand dependency rate of a product on its complementary product price (λ) is assumed to be the same for both product types. In reality, the demand dependency rate of a product type on its own price is more than that of its complementary product, i.e. $\beta_i > \lambda$.

2. Both product types are produced on the same production line and the vendor can afford the demand of buyer. In other words, Eq. (2) is valid:

$$\sum_{i=1}^{2} \frac{\alpha_i}{P_i} \leqslant 1 \tag{2}$$

3. A continuous inventory review policy is used for both products at the buyer. Moreover, the inventory planning of the products are independent of each other.
4. The vendor produces n_iQ_i of each product type after each setup time and delivers them to the buyer in n_i batches.