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Supply chain coordination: A game-theory approach

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Abstract

In a supply chain organized as a network of autonomous enterprises, the main objective of each partner is to optimize his production and supply policy with respect to his own economic criterion. Conflicts of interests and the distributed nature of the decision structure may induce a global loss of efficiency. Contracts can then be used to improve global performance and decrease risks. The purpose of the paper is to evaluate the efficiency of different types of contracts between the industrial partners of a supply chain. Such an evaluation is made on the basis of the relationship between a producer facing a random demand and a supplier with a random lead-time. The model combines queuing theory for evaluation aspects and game theory for decisional purposes.

Keywords: Game theory; Manufacturing systems; Supply chains; Queuing networks; Optimization; Markov processes; Inventory control

1. Introduction

The supply chains considered cover different enterprises sharing common information and logistic networks. Due to the distributed nature of the system and the decisional autonomy of heterogeneous decision centers, organization of tasks and activities raises some specific problems of coordination and integration.

Enterprises can be seen as players in a game defined by a common goal, but separate constraints and conflicting objectives. Taking into consideration that the entities of a supply chain need to cooperate in order to achieve the global goal, a problem appears: how to cooperate without knowing the internal models of the other entities involved? In order to obtain acceptable trade conditions, a certain form of negotiation turns out to be necessary. Game theory provides a mathematical background for modeling the system and generating solutions in competitive or conflicting situations. The basic rationality principle of game theory states that each player acts to optimally accomplish his/her individual goal, taking into account that the others play in the same manner. However, if the individual goal of each player is only to maximize his gain or to minimize his loss, the agreements obtained by negotiation may be fragile and will not generally guarantee global optimality for the whole supply chain, particularly when external demand is stochastic. For these reasons, much effort has been recently devoted to conceiving contracts strengthening the commitments of partners through risk, profit or cost sharing, and/or moving the equilibrium state of the game toward a better global performance. Game-theoretical applications in supply chain management are reviewed by Cachon and Netessine (2004) and Leng and Parlar (2005). Cachon (2003) reviews the literature on supply chain coordination with contracts. Examples of contract parameters that can be used to achieve coordination, are quantity discounts, returns (buybacks), quantity flexibility, and the use of subsidies/penalties. Gupta and Weerawat (2005) consider the interactions between an end-product manufacturer and an intermediate-product supplier, assuming that the manufacturer has no inventory for end-products. They describe revenue sharing contracts able to coordinate this supply chain. Gupta et al. (2004) generalize this study to a system in which the manufacturer has an inventory for end-products. They propose revenue and cost-sharing contracts with a delay penalty for the supplier in case of a late

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delivery by the manufacturer. They also construct a search technique in a closed interval to compute the optimal base stock value for the manufacturer.

This paper presents several types of contracts between a producer and a supplier: price-only contracts, backorder costs sharing through transfer payments, capacity reservation to assure supply. Each contract is characterized by several parameters, whose values are to be determined through optimization and negotiation, using a simple analytical model described in the following section. Due to the use of such a general but somewhat simplistic model, application of the results to a real system would require complementary studies by simulation, tests and measurements. However, it is believed that the decisional levers studied in the paper are relevant in most applied cases. It is mainly the optimal values of decision variables that remain to be calculated in practical applications.

2. Model and analysis

The basic supply chain element considered in the paper consists of one producer and one supplier. Such an element is considered generic in terms of trade agreements and product flows within a supply chain. The producer manufactures and delivers goods to the customers using raw products delivered by his supplier.

2.1. Basic assumptions

Manufacturing and delivery times of the producer are supposed negligible relatively to delivery time from the supplier. Classically, the bill of materials applies to determine the quantity of components necessary per unit of final product. But for simplicity of notations, a one-to-one correspondence in technical coefficients is assumed between the considered component and the final product. Both demand and delivery processes are supposed random with respective average rates λ and μ. Parameter λ is exogenous. Demand is supposed stationary with an average rate, λ, supposed known by the producer. Parameter μ is the main operational decision variable for the supplier. It measures the production capacity devoted to this producer. It is also one of the basic negotiation parameters between the supplier and the producer.

An additional decision variable for the producer is the reference inventory level of finite products, S. The producer is supposed to use an order-driven base stock policy. When an order comes to her, it is immediately satisfied if its amount is available in the stock. If not, it has to wait until the inventory has been sufficiently replenished by the arrival of products from the supplier. In both cases, an order is placed from the producer to the supplier whenever a demand comes and has the same amount (1 in the unitary case). Such a base stock control policy can also be interpreted as a Kanban mechanism (Buzacott and Shantikumar, 1993). After an initial inventory replenishment stage, the inventory position is held constant with value S. At time t, the two random variables; the current inventory level $I(t)$ and the number of uncompleted orders $u(t)$ are linked by the relation

$$I(t) + u(t) = S. \tag{1}$$

It can be noted that under the considered inventory policy, $u(t)$ also represents the current queue length of orders for the supplier.

Consider the following notations: I is the random variable representing the producer inventory level in stationary conditions, u the random variable representing the number of uncompleted orders from the producer not yet delivered by the supplier in stationary conditions, h the unit holding cost, b the unit backorder cost, p the retail price, c_s the supplier production cost per unit, c_p the producer production cost per unit.

Let $T(\lambda, \mu, S)$ be the expected transfer payment rate from the producer to the supplier. That function may depend on a number of quantities, according to the contract considered.

2.2. The M/M/1 model

Consider now the model of a unitary demand occurring according to a Poisson process with rate λ. The supplier delivery time is modeled as an exponentially distributed service time with mean value $1/\mu$, satisfying the stability condition $\rho = \lambda/\mu < 1$. Under the $(S-1, S)$ base stock policy, the inventory position is a constant with value S and the number of uncompleted orders, $u(t)$, represents the queue length of orders for the supplier (Arda and Hennet, 2006). It is a simple M/M/1 system with birth–death coefficients (λ, μ). Accordingly, due to Eq. (1), the inventory level $I(t)$ is a Markov chain described by the transition graph of Fig. 1.

In stationary conditions, $P_w = \mathrm{Prob}(u = w) = \mathrm{Prob}(I = S - w) = \rho^w(1-\rho)$.

The expected value of u is defined by

$$Z = E[u] = \sum_{w=0}^{\infty} w P_w. \tag{2}$$

It corresponds to the expected number of customers in the M/M/1 queuing system, $Z = \rho/1-\rho$. Then, from Little's law, the expected delivery time for the producer is

$$\tau = \frac{1}{\mu - \lambda}. \tag{3}$$

It is assumed that demands arriving when the stock is empty are backordered, and a backorder cost, b, is associated with each unit rate of backordered sales. Let F be the discrete distribution function of u, and $\overline{F}(u) = 1 - F(u)$. The probability of backorder is

$$\mathrm{Prob}(I \leqslant 0) = \mathrm{Prob}(u \geqslant S) = \overline{F}(S) = \rho^S. \tag{4}$$

The expected amount of backorders is

$$L(\lambda, \mu, S) = \sum_{w=S}^{\infty} (w - S) P_w = \frac{\rho^{S+1}}{1-\rho}, \tag{5}$$