Computers & Industrial Engineering 57 (2009) 368–382

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Stackelberg game-theoretic model for optimizing advertising, pricing and inventory policies in vendor managed inventory (VMI) production supply chains

Yugang Yu [a,c], George Q. Huang [b,*], Liang Liang [d]

[a] Rotterdam School of Management, Erasmus University, The Netherlands
[b] Department of Industrial and Manufacturing Systems Engineering, University of Hong Kong, PR China
[c] Management School, Lanzhou University, PR China
[d] Management School, University of Science and Technology of China, PR China

ARTICLE INFO

Article history:
Received 4 October 2005
Received in revised form 8 November 2006
Accepted 10 December 2008
Available online 24 December 2008

Keywords:
Supply chain management
Vendor managed inventory
Stackelberg game theory

ABSTRACT

This paper discusses how a manufacturer and its retailers interact with each other in order to optimize their individual net profits by adjusting product marketing (advertising and pricing) and inventory policies in an information-asymmetric VMI (vendor managed inventory) supply chain. The manufacturer produces and supplies a single product at the same wholesale price to multiple retailers who then sell the product in dispersed and independent markets at retail prices. The demand rate in each market is an increasing and concave function of the advertising investments of both local retailers and the manufacturer, but a decreasing and convex function of the retail prices. The manufacturer determines its wholesale price, its advertising investment, replenishment cycles for the raw materials and finished product, and backorder quantity to maximize its profit. Retailers in turn consider the replenishment policies and the manufacturer's promotion policies and determine the optimal retail prices and advertisement investments to maximize their profits. This problem is modeled as a Stackelberg game where the manufacturer is the leader and retailers are followers. An algorithm has been proposed to search the Stackelberg equilibrium. A numerical study has been conducted to demonstrate how the algorithm works and to understand the influences of decision variables and/or parameters. Several research questions are examined, including under what circumstances the retailers and manufacturer should increase their advertising expenditures and/or reduce the retail prices and what actions should be taken if the prices of raw materials or their holding costs increase.

1. Introduction

This paper considers a supply chain with one manufacturer (vendor) and multiple retailers who are involved in producing, delivering and selling only one type of finished product. The manufacturer purchases multiple components or raw materials according to the BOM (bill of materials) of the finished product, produces the finished product and distributes it to its retailers. This supply chain therefore has three levels of retailers, the manufacturer, and the suppliers of raw materials (e.g. Munson & Rosenblatt, 2001). Each retailer buys the product from the manufacturer at the wholesale price, and then sells it to its consumer market at a retail price. Retailers' markets are assumed to be geographically dispersed and independent of each other. Therefore, the competition and transshipment between the regional retailers are omitted. The demand rate in each local retail market is assumed to be an increasing function of the advertising investments made by the corresponding local retailer and the manufacturer, and a decreasing function of the retail price.

This supply chain is considered "cooperative" in two senses. Firstly, both the manufacturer and retailers contribute to the advertising expenditure with the common goal to increase the demand and an increasing demand is of benefit of both of them. Secondly, both the manufacturer and retailers coordinate their efforts in managing the inventory of finished products. In particular, the VMI (vendor managed inventory) strategy is arranged between them. In a VMI supply chain system, the vendor decides on the appropriate inventory levels of each of the products (within previously agreed upon bounds), and the appropriate inventory policies to maintain these levels (Simchi-Livi, Kaminsky, & Simchi-Livi, 2000). That is, the retailers' inventories are managed by the manufacturer who charges a cost per unit for this. Under the VMI arrangement, the manufacturer compensates its retailers for inventory and backorder costs in order to eliminate the influence of variations in the replenishment cycle while each retailer is only responsible for the inventory cost for the product items that it sells. That is, the inventory cost of each retailer is proportional to its demand rate. The manufacturer also manages its own inventory of finished product that is not yet shipped. In addition, the raw material inventory for the manufacturer is also considered.

* Corresponding author.
E-mail address: gqhuang@hku.hk (G.Q. Huang).

0360-8352/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cie.2008.12.003

Nomenclature

Indices

m number of retailers
$i = 1,2,\ldots,m$ index of the retailers or markets
l number of raw materials
$j = 1,2,\ldots,l$ index of raw materials

Decision variables of retailer i, i = 1,2,…,m

a_i advertising investment for retailer i ($/time)
p_i retail price charged by retailer i ($/unit)

Decision variables of the manufacturerA

advertising investment for manufacturer ($/time)
b_i fraction of backlogging rate in a cycle for retailer i ($/time)
C common replenishment cycle time for the finished product
c_p wholesale price of the finished product set by the manufacturer ($/unit)
n_j cycle factor n_j for raw material j which is an integer. n_jC represents the order/procurement cycle time for raw material j

Parameters

c_m manufacturing cost for per unit finished product ($/unit)
c_{rj} price for per unit raw material j ($/unit)
H_{bi} holding cost paid by the manufacturer at retailer i's side ($/unit/time)
H_p holding cost per unit finished product of inventory at the manufacturer's side ($/unit/time)
H_{rj} holding cost per unit raw material j at the manufacturer ($/unit/time)
K_i a positive constant representing the market scale of retailer i in the Cobb–Douglas function
L_{bi} backorder cost paid by the manufacturer to retailer i's side ($/unit/time)
M_j the usage factor of raw material j representing the quantity of raw material j required for producing each finished product
P production rate of the finished product for the manufacturer, which is a known constant and $\sum_{i=1}^{m} D_i(p_i, a_i, A) \leqslant P$
S_{bi} fixed order cost paid by the manufacturer for retailer i's side ($ for one time)
S_p fixed order cost for a common cycle time for the finished product at the manufacturer's side ($/order setup)
S_{rj} fixed order cost for the procurement of raw material j ($/order setup)
ϕ_i transportation cost per unit finished product shipped from the manufacturer to retailer i ($/unit)
ζ_i inventory cost for retailer i ($/unit/time)
α_i retailer i's advertising (a_i) elasticity of demand in the Cobb–Douglas function
β_i the manufacturer's advertising (A) elasticity of the demand in the Cobb–Douglas function
ρ_i the price elasticity of retailer i's demand in the Cobb–Douglas function

Functions

CC_i compensating cost for the manufacturer to retailer i ($/time)
$D_i(p_i, a_i, A)$ demand rate of the finished product in market i served by retailer i, a decreasing and convex function of p_i and an increasing and concave function of a_i and A (unit/time)
HIC_{rj} total holding inventory cost for raw material j ($/cycle)
TDC_p total direct cost for the finished product ($/time)
TIC_r total inventory cost for all raw materials ($/time)
TIC_p total inventory cost for the finished product ($/time)
TIC total inventory cost for the finished product and raw materials ($/time)
$TIDC_p$ total indirect cost for the finished product ($/time)
NP_{bi} net profit for retailer i ($/time)
NP_m net profit for the manufacturer ($/time)

This supply chain is also considered "competitive" in the sense that individual enterprises in the supply chain have their own objectives and decisions to optimize. During the optimization process, it is important to note that some degrees of autonomies must be retained for individual enterprises to make decisions in order to respond to their changing environments. For example, individual enterprises enjoy the rights of determining product prices, and advertising investments in promoting the product. In the supply chain, the retailers are able to determine the retail prices and advertising investments according to their own market environments to maximize their own profits. The manufacturer is able to determine its own advertising investment, wholesale price, replenishment cycle for raw materials and the finished product, and backorder quantity to maximize its own profit.

Such combination of "competitive" and "cooperative" has been found in real-life successful VMI partnerships, such as the partnership between Wal-Mart and Procter & Gamble (P&G) (Buzzell & Ortmeyer, 1995), among the distribution systems of Dell, HP and ST Microelectronics (Shah, 2002; Tyan & Wee, 2003), and Barilla distribution system in Europe (Hammond, 2003). Manufacturers produce and distribute products for their buyers. For example, HP sells printers, computers and scanners. P&G produces cosmetics, household cleaners and paper products. Barilla makes foods. They confront a common problem: how to optimally determine their advertising, pricing, and inventory policies in order to maximize their profits. During the VMI decision process, the manufacturer knows about its retailers' inventory and market demand information. Its profit is influenced by pricing and advertising decisions, not only of itself but also of its retailers. With its inventory managed by the manufacturer, each retailer responds to the manufacturer's decisions to maximize its retail profit.

This paper adopts the approach of modelling the supply chain as a Stackelberg game (Chen, Federgruen, & Zheng, 2001; Lau & Lau, 2004; Lau, Lau, & Zhou, 2007). Because the manufacturer manages the finished product inventories for all its retailers, it is treated as the leader dominating the supply chain and the retailers as followers. As the leader, the manufacturer, knowing about the action of each retailer, optimizes its advertising investment, wholesale price, replenishment cycles for raw materials and the finished product, and backorder quantity with the objective of maximizing its own profit. As followers, each retailer takes the manufacturer's optimal decisions as input parameters to determine the retail price and advertising investment by maximize its own profit. The resulting overall optimal solution for the supply chain is referred to as the Stackelberg equilibrium.

Stackelberg game is used in this paper to address the question how enterprises in the supply chain work together to maximize