Product quality, eco-friendly improvement and pricing decisions in a two-echelon supply chain under consumer environmental awareness

Nikunja Mohan Modak
Palpara Vidyamandir
Chakdaha-741222, West Bengal, India

***Peter Kelle** (qmkell@lsu.edu)*
Stephenson Department of Entrepreneurship & Information Systems
Louisiana State University, Baton Rouge, USA

Abstract

This paper explores the effects of consumers' environmental and quality awareness on supply chain management. We consider a manufacturer-retailer supply chain where the demand depends on price, quality, and eco-friendly level of the product. Both centralized and decentralized models are developed to maximize the total supply chain and individual members' profit respectively. Decentralized decisions are determined under Stackelberg game setting. Price, quality level, and eco-friendly level of the product are considered as decision variables. Finally, a two part tariff contract is used to coordinate the supply chain and eliminate inefficiencies of decentralized decisions.

Keywords: Eco-friendly Supply Chain, Product quality, Coordination

Introduction

Business firms are increasingly realizing the benefits of adopting environmental responsibility and including it into their supply chain strategy and operations. This paper quantifies the effects of customers' environmental and quality awareness on supply chain management. Teng and Thompson (1996) proposed a mathematical model considering quality and price as decision variables. Banker et al. (1998) assumed that the demand function is linear in price and product quality. Glock et al. (2012) considered the environmental impact of the production process as a quality attribute and showed that by controlling scrap and emissions, the manufacturer can attract additional customers and increase its profit. Liu et al. (2012) investigated the impact of consumers' environmental awareness on the profitability of manufacturers and retailers from a supply chain network perspective. They assumed that demand of the product depends on selling price and the eco-friendly level of the product. Higher quality of a product leads to higher level of customers' satisfaction and hence to higher demands (Modak et al., 2018).

The coordination among channel members is essential to improve supply chain's performance and so it is a very important strategic issue in supply chain management (Choi, 2011 and Chiu et al, 2016). Coordination mechanism is used to eliminate the so called 'double marginalization' problem of decentralized channel. Existing literature has rich content in different types supply chain coordination mechanism, for example, quantity discount (Li and Liu 2006), two-part tariff (Modak et al., 2016a), revenue sharing (Panda et al., 2017), buyback (Wu, 2013), profit sharing (Modak et al., 2016b), etc. In several research studies two-part tariff is used as a coordination contract scheme (Moorthy, 1987; Qi et al., 2010). In this contract, manufacturer sells products to retailer at a discounted wholesale price and charges the retailer a fixed franchise fee, which was agreed beforehand through a contract.

We consider a manufacturer-retailer-customer supply chain where the customers' demand of the product depends on the price, quality, and eco-friendly level of the product. Both centralized and decentralized models are developed to maximize the total supply chain profit and individual members' profit respectively. Decentralized decisions are determined under Stackelberg game setting. Price, quality level, and eco-friendly level of the product are considered as decision variables. Finally, the channel coordination problem between the manufacturer and the retailer is investigated using two part tariff contract.We discuss the following managerial questions: What is the effect of the cost parameters on the optimal quality level and eco-friendly level of the product? How does the awareness of consumers about environment affect the optimal decision? How to coordinate decentralized channel to eliminate double marginalization?

Notations & Assumptions

Cost factors

c_m	unit marginal cost of manufacturer per unit product,
c_t	technological cost of manufacturer,
π_m	profit function of the manufacturer,
π_r	profit function of the retailer.

Decision variables

w	per unit product wholesale price of manufacturer,
p	retail price of the product,
q	quality level of product,
e	eco-friendly level of product.

Other parameters

D	demand of the product,
q_{min}	minimum quality level of product,
a_0	market potential,
b	price sensitivity of demand,
α	elasticity factor of eco-friendly level of product in demand,
a_1	elasticity factor of quality level of product in demand,
k_1	scaling parameter of product quality associated with technological cost,
k_2	scaling parameter of eco-friendly level of product associated with technological cost,
k_0	fixed minimum cost of technology for minimum quality level and eco-friendly level of the product ,
c_1	influencing parameter of product quality associated with unit marginal cost of manufacturer,
γ	influencing parameter of product's eco-friendly level associated with unit marginal cost of manufacturer,

Assumptions

1. End consumers' demand depends on retail price, quality level and eco-friendly level of product: $D = a_0 + a_1(q - q_{min}) - bp + \alpha e$. Linear price and quality dependent demand is common and well-established in supply chain literature (Modak et al., 2018; Glock et al., 2012; Teng and Thompson, 1996).
2. Unit marginal cost (c_m) and technological cost (c_t) of the manufacturer depends on quality level and eco-friendly level of the product and are given by $c_m = c_0 + c_1(q - q_{min}) + \gamma e$ and $c_t = k_0 + k_2 e^2 + k_1(q - q_{min})^2$.
3. For feasibility and non-negativity of the demand, we assume that $a_0 - bc_0 > 0$, $\alpha > b\gamma$ and $p \leq [a_0 + a_1(q - q_{min}) + \alpha e]/b$.
4. Lead time is assumed equal to zero, i.e., the product flows from the manufacturer to the retailer without any delay when demand occurs. The manufacturer follows lot-for-lot policy.

Mathematical Modeling

Consider a two levels supply chain, where the manufacturer produces the product at a unit cost c_m and supplies it to the retailer in a single batch at a wholesale price w. The retailer sells the product to customers at a retail price p. Model examines the effects of the consumers' environmental and quality awareness on the channel members' profitability from a supply chain network perspective. Under this model setting next section develops two mathematical models under decentralized and centralized decision making context.

Decentralized Decision

The manufacturer and the retailer are independent in decentralized structure and they try to maximize their own expected profits without considering the total supply chain profit. The manufacturer acts as the Stackelberg leader and the retailer acts as the follower. For a wholesale price, w, the profit function of the manufacturer and the retailer are given by

$$\pi_m = (w - c_m)D - k_0 - k_1(q - q_{min})^2 - k_2 e^2 \tag{1}$$

$$\pi_r = (p - w)D \tag{2}$$

Under Stackelberg game settings, we solve the model to find optimal outcomes using the backward induction method. Solving the necessary condition to maximize π_r, i.e., solving $d\pi_r/dp = 0$ we get

$$p = \frac{a_0 + a_1(q - q_{min}) + bw + e\alpha}{2b} \tag{3}$$

Moreover note that, $d^2\pi_r/dp^2 = -2b < 0$, confirms the concavity of π_r. Then, substituting optimal value of retailer's selling price in (1) and solving the necessary conditions to maximize π_m, i.e., solving $d\pi_m/dw = 0$, $d\pi_m/de = 0$ and $d\pi_m/dq = 0$, we get optimal value of the manufacturer's decision variables and are provided in Proposition 1(i). Substituting the manufacturer's optimal decision we have the optimal selling price, demand, and profit of the manufacturer and the retailer and they are given in Proposition 1(ii).

Proposition 1. *(i)* Optimal wholesale price, quality level and eco-friendly level of the product are given by

$$w^* = \frac{a_1(a_0+bc_0)c_1k_2+c_0k_1(4bk_2-\alpha^2+b\alpha\gamma)+a_0(4k_1k_2+k_1\alpha\gamma-bk_1\gamma^2-bc_1{}^2k_2)-a_1{}^2c_0k_2}{(2bk_1(4k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1{}^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} \quad (4)$$

$$e^* = \frac{(a_0-bc_0)k_1(\alpha-b\gamma)}{(2bk_1(4k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1{}^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} \quad (5)$$

$$q^* = q_{min} + \frac{(a_0-bc_0)(a_1-bc_1)k_2}{(2bk_1(4k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1{}^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} \quad (6)$$

(ii) *Optimal demand and profit of the manufacturer and the retailer are given by*

$$p^* = \frac{a_1(a_0+bc_0)c_1k_2+c_0k_1(2bk_2-\alpha^2+b\alpha\gamma)+a_0(6k_1k_2+k_1\alpha\gamma-bk_1\gamma^2-bc_1{}^2k_2)-a_1{}^2c_0k_2}{(2bk_1(4k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1{}^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} \quad (7)$$

$$\mathrm{D}^* = \frac{2b(\mathrm{a}_0-b\mathrm{c}_0)\mathrm{k}_1\mathrm{k}_2}{(2b\mathrm{k}_1(4\mathrm{k}_2+\alpha\gamma)+2\mathrm{a}_1b\mathrm{c}_1\mathrm{k}_2-b^2(\mathrm{c}_1{}^2\mathrm{k}_2+\mathrm{k}_1\gamma^2)-\mathrm{a}_1^2\mathrm{k}_2-\mathrm{k}_1\alpha^2)} \quad (8)$$

$$\pi_m{}^* = \frac{(\mathrm{a}_0-b\mathrm{c}_0)^2\mathrm{k}_1\mathrm{k}_2}{(2b\mathrm{k}_1(4\mathrm{k}_2+\alpha\gamma)+2\mathrm{a}_1b\mathrm{c}_1\mathrm{k}_2-b^2(\mathrm{c}_1{}^2\mathrm{k}_2+\mathrm{k}_1\gamma^2)-\mathrm{a}_1^2\mathrm{k}_2-\mathrm{k}_1\alpha^2)} - \mathrm{k}_0 \quad (9)$$

$$\pi_r{}^* = \frac{4b(\mathrm{a}_0-b\mathrm{c}_0)^2\mathrm{k}_1{}^2\mathrm{k}_2{}^2}{(2b\mathrm{k}_1(4\mathrm{k}_2+\alpha\gamma)+2\mathrm{a}_1b\mathrm{c}_1\mathrm{k}_2-b^2(\mathrm{c}_1{}^2\mathrm{k}_2+\mathrm{k}_1\gamma^2)-\mathrm{a}_1^2\mathrm{k}_2-\mathrm{k}_1\alpha^2)^2} \quad (10)$$

To check the sufficient conditions of concavity of profit function of the manufacturer, the corresponding Hessian matrix, H is calculated as follows

$$H = \begin{pmatrix} \frac{\partial^2\pi_m}{\partial w^2} & \frac{\partial^2\pi_m}{\partial w\partial e} & \frac{\partial^2\pi_m}{\partial w\partial q} \\ \frac{\partial^2\pi_m}{\partial e\partial w} & \frac{\partial^2\pi_m}{\partial e^2} & \frac{\partial^2\pi_m}{\partial e\partial q} \\ \frac{\partial^2\pi_m}{\partial q\partial w} & \frac{\partial^2\pi_m}{\partial q\partial e} & \frac{\partial^2\pi_m}{\partial q^2} \end{pmatrix} = \begin{pmatrix} -b & \frac{(\alpha+b\gamma)}{2} & \frac{(a_1+bc_1)}{2} \\ \frac{(\alpha+b\gamma)}{2} & -2k_2-\alpha\gamma & \frac{-(a_1\gamma+\alpha c_1)}{2} \\ \frac{(a_1+bc_1)}{2} & \frac{-(a_1\gamma+\alpha c_1)}{2} & -2k_1-a_1c_1 \end{pmatrix}$$

$$\det[\mathrm{H}] = -\frac{1}{2}[2b\mathrm{k}_1(4\mathrm{k}_2+\alpha\gamma)+2\mathrm{a}_1b\mathrm{c}_1\mathrm{k}_2-b^2(\mathrm{c}_1{}^2\mathrm{k}_2+\mathrm{k}_1\gamma^2)-\mathrm{a}_1^2\mathrm{k}_2-\mathrm{k}_1\alpha^2]$$

If the principal minors are alternatively negative and positive, i.e., the kth order leading principal minor Δ_k follows the sign of *(-1)*^{k}, then the profit function of the manufacturer will be concave. Note that, $\Delta_1 = \frac{\partial^2\pi_m}{\partial \mathrm{w}^2} = -\mathrm{b} < 0$, $\Delta_2 = det\begin{bmatrix} -b & \frac{(\alpha+b\gamma)}{2} \\ \frac{(\alpha+b\gamma)}{2} & -2\mathrm{k}_2-\alpha\gamma \end{bmatrix} = \mathrm{b}(2\mathrm{k}_2+\alpha\gamma) - \frac{(\alpha+b\gamma)^2}{4}$, and $\Delta_3 = \det[H] = -\frac{1}{2}[2b\mathrm{k}_1(4\mathrm{k}_2+\alpha\gamma)+2\mathrm{a}_1b\mathrm{c}_1\mathrm{k}_2-b^2(\mathrm{c}_1{}^2\mathrm{k}_2+\mathrm{k}_1\gamma^2)-\mathrm{a}_1^2\mathrm{k}_2-\mathrm{k}_1\alpha^2]$. Now, $\Delta_2 > 0$ if $4\mathrm{b}(2\mathrm{k}_2+\alpha\gamma)-(\alpha+\mathrm{b}\gamma)^2 > 0$ and $\Delta_2 < 0$ if $[2b\mathrm{k}_1(4\mathrm{k}_2+\alpha\gamma)+2\mathrm{a}_1b\mathrm{c}_1\mathrm{k}_2-b^2(\mathrm{c}_1{}^2\mathrm{k}_2+\mathrm{k}_1\gamma^2)-\mathrm{a}_1^2\mathrm{k}_2-\mathrm{k}_1\alpha^2] > 0$. Hence, concavity condition of the manufacturer profit function is summarized in the Proposition 2.

Proposition 2. *The profit function of the manufacturer is a concave function of w, q and e if* $[2bk_1(4k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1{}^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2] > 0$ *and* $4b(2k_2+\alpha\gamma) > (\alpha+b\gamma)^2$

Note that, four cost parameters k_1, k_2, c_1 and γ have similar impact on optimal quality level and eco-friendly level of the product (see appendix 1 and figure 1.) Optimal quality level and eco-friendly level of the product decrease with the increment of cost parameters.

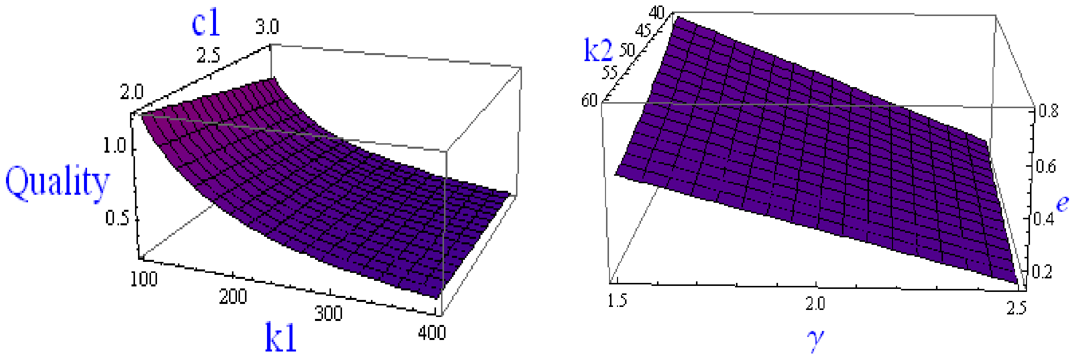

Figure 1. Effect of cost parameters on optimal quality and eco-friendly level of the product.

Moreover note that, optimal demand, profit of the manufacturer and profit of the retailer decrease if cost parameters increase (see appendix 2). The reason is straight forward because higher value of cost parameters will decrease the quality level and eco-friendly level of the product, as result it will decline end consumers' demand and so profit of the channel members will also decrease.

Centralized Decision

Under centralized decision making, all actions are prepared by one decision maker or alternatively, all the channel members are willing to cooperate and want to implement a joint decision. The profit function of the centralized channel is given by

$$\pi_c = (p - c_m)D - k_0 - k_1(q - q_{min})^2 - k_2 e^2 \qquad (11)$$

Proposition 3. *The profit function of* the centralized channel *is a concave function of w, q and e if* $[2bk_1(2k_2 + \alpha\gamma) + 2a_1 bc_1 k_2 - b^2({c_1}^2 k_2 + k_1\gamma^2) - a_1^2 k_2 - k_1\alpha^2] > 0$ *and* $4b(k_2 + \alpha\gamma) > (\alpha + b\gamma)^2$

Proof:

The Hessian matrix, H_c of the centralized channel profit function is calculated as follows

$$H_c = \begin{pmatrix} -2b & (\alpha + b\gamma) & (a_1 + bc_1) \\ (\alpha + b\gamma) & -2k_2 - 2\alpha\gamma & -(a_1\gamma + \alpha c_1) \\ (a_1 + bc_1) & -(a_1\gamma + \alpha c_1) & -2k_1 - 2a_1 c_1 \end{pmatrix}$$

Note that, if the principal minors of H_c are alternatively negative and positive, i.e., the kth order leading principal minor Δ_{ck} follows the sign of *(-1)*^{k}, then the profit function of the channel will be concave. Notice that, $\Delta_{c1} = \frac{\partial^2 \pi_c}{\partial p^2} = -2b < 0$, $\Delta_{c2} = det\begin{bmatrix} -2b & (\alpha + b\gamma) \\ (\alpha + b\gamma) & -2k_2 - 2\alpha\gamma \end{bmatrix} = 4b(k_2 + \alpha\gamma) - (\alpha + b\gamma)^2$, and $\Delta_{c3} = \det[H_c] = -2[2bk_1(2k_2 + \alpha\gamma) + 2a_1 bc_1 k_2 - b^2({c_1}^2 k_2 + k_1\gamma^2) - a_1^2 k_2 - k_1\alpha^2]$. Now, $\Delta_{c2} > 0$ if $4b(2k_2 + \alpha\gamma) - (\alpha + b\gamma)^2 > 0$ and $\Delta_{c3} < 0$ if $[2bk_1(2k_2 + \alpha\gamma) + 2a_1 bc_1 k_2 - b^2({c_1}^2 k_2 + k_1\gamma^2) - a_1^2 k_2 - k_1\alpha^2] > 0$. Hence, we have the concavity conditions of the centralized channel profit function which is summarized in the Proposition 3.

Solving the necessary conditions to maximize π_c, i.e., solving $d\pi_c/dp = 0$, $d\pi_c/de = 0$ and $d\pi_c/dq = 0$, we get optimal value of the centralized channel and are provided in proposition 4(i). Substituting optimal decision we have optimal *demand and profit of the channel* and are given in proposition 4(ii).

Proposition-4: *(i)* Optimal selling price, quality level and eco-friendly level of the product are given by

$$p_c^* = \frac{a_1(a_0+bc_0)c_1k_2+c_0k_1(2bk_2-\alpha^2+b\alpha\gamma)+a_0(2k_1k_2+k_1\alpha\gamma-bk_1\gamma^2-bc_1^2k_2)-a_1^2c_0k_2}{(2bk_1(2k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} \quad (12)$$

$$e_c^* = \frac{(a_0-bc_0)k_1(\alpha-b\gamma)}{(2bk_1(2k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} \quad (13)$$

$$q_c^* = q_{min} + \frac{(a_0-bc_0)(a_1-bc_1)k_2}{(2bk_1(2k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} \quad (14)$$

(ii) *Optimal demand and profit of the manufacturer and the retailer are given by*

$$D_c^* = \frac{2b(a_0-bc_0)k_1k_2}{(2bk_1(2k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} \quad (15)$$

$$\pi_c^* = \frac{(a_0-bc_0)^2k_1k_2}{(2bk_1(2k_2+\alpha\gamma)+2a_1bc_1k_2-b^2(c_1^2k_2+k_1\gamma^2)-a_1^2k_2-k_1\alpha^2)} - k_0 \quad (16)$$

Note that, $\pi_c^* - (\pi_m^* + \pi_r^*) = \frac{16b^2(a_0-bc_0)^2k_1^3k_2^3}{T_cT_d^2} > 0$. Where $T_c = [2bk_1(2k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2(c_1^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]$ and $T_d = [2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2(c_1^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]$. The result clearly showing that centralized channel always outperforms decentralized channel. Decentralized channel suffers due to the problem of double marginalization. To remove the double marginalization and to get maximum outcome, next section discusses how to coordinate the decentralized channel.

Supply Chain Coordination

For channel coordination, we apply two-part tariff contract. Suppose that the manufacturer supplies the product to the retailer at all-unit discount price φw^* ($\varphi \le 1$) where w^* is expressed in Proposition 1, and charges a franchise fee f. Then the profit function of retailer and manufacturer are as

$$\pi_m = (\varphi w^* - c_m)D - k_0 - k_1(q - q_{min})^2 - k_2e^2 + f \quad (17)$$

$$\pi_r = (p - \varphi w^*)D - f \quad (18)$$

Under the Stackelberg game settings, first the retailer determines the selling price under the two-part tariff contract. Then based on it the manufacturer determines the wholesale prices and franchise fee. Using the necessary condition for the existence of optimal solution, optimal selling prices of the retailer under two-part tariff contract can be found as $p_{co} = \frac{a_0+a_1qc+ec\alpha+bw_d\phi}{2b}$. Now, the channel will be coordinated if the retailers self-optimized selling price under the proposed contract coincide with the respective centralized selling prices, that is, $p_{co} = p_c^*$. Solving the equation, $p_{co} - p_c^* = 0$, we get optimal discount rate (φ^*) and is given in proposition 5. The manufacturer and the retailer jointly implement coordination contract when it assures win–win outcomes i.e., they receive more than their respective decentralized profit. Comparison of profits of the channel members under the proposed coordination contract with the decentralized one provides range of franchise fee and is provided in the following proposition.

Proposition 5. *Two-part tariff contract coordinates the supply chain and provides a win-win opportunity for both channel members for a discount rate φ^* and franchise fee f in the range (f^{min}, f^{max}), where*

$$\varphi^* = \frac{a_1{}^2c_0k_2 - a_1(a_0+bc_0)c_1k_2 + a_0bc_1{}^2k_2 - 4bc_0k_1k_2 + c_0k_1\alpha^2 - (a_0+bc_0)k_1\alpha\gamma + a_0bk_1\gamma^2}{w^*(2bk_1(2k_2+\alpha\gamma) + 2a_1bc_1k_2 - b^2(c_1{}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2)} \tag{19}$$

$$f^{min} = \pi_m{}^* - \frac{(a_0-bc_0)^2k_1k_2(2bk_1\alpha\gamma - (a_1-bc_1)^2k_2 - k_1\alpha^2 - b^2k_1\gamma^2)}{(2bk_1(2k_2+\alpha\gamma) + 2a_1bc_1k_2 - b^2(c_1{}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2)^2} + k_0 \tag{20}$$

$$f^{max} = \frac{4b(a_0k_1k_2 - bc_0k_1k_2)^2}{(2bk_1(2k_2+\alpha\gamma) + 2a_1bc_1k_2 - b^2(c_1{}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2)^2} - \pi_r{}^* \tag{21}$$

Figure 2 depicts that optimal discount rate increases if demand elasticity parameters associated with quality and eco-friendly level of product increase.

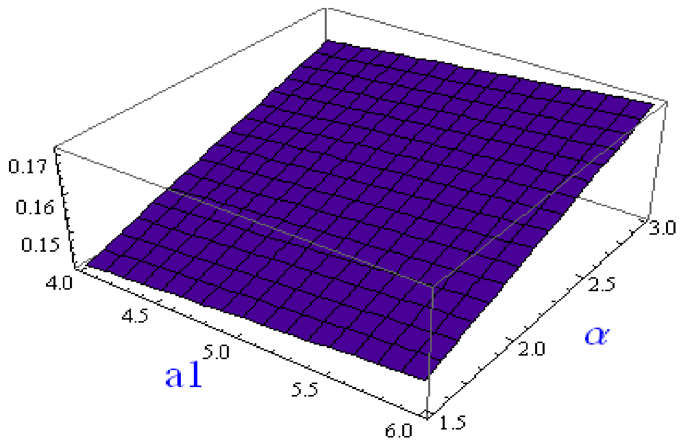

Figure 2. Effect of demand elasticity parameters of quality and eco-friendly level on φ^*

Conclusions

This paper determines the optimal selling price, quality level and eco-friendly level for the objective of profit maximization in a decentralized and centralized system under deterministic demand environment. The effects of cost and demand elasticity parameters are analyzed. Centralized channel always outperform decentralized channel as there is no 'double marginalization' having a single decision maker. The manufacturer provides all-unit discount on the wholesale price to motivate the retailer to order the optimal centralized order quantity. On the other hand, the franchise fee is used to eliminate channel conflict. The proposed two-part tariff contract can be implemented successfully if all the channel members get win-win outcome that is ensured if the franchise fee is in the range we quantified.

The present model can be extended in several directions. The concept can be examined under different channel structures with competitive manufacturers, duopoly retailers and multiple retailers. The single-period setting could be extended to a multi-period inventory model. The interaction between the retailer and the manufacturer can be studied under Nash game and evolutionary game. Another extension to this research can be the consideration of uncertainty in demand.

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Appendix-1

$$\frac{de^*}{dk_1} = -\frac{(a_0 - bc_0)(\alpha - b\gamma)(\mathrm{a}_1 - bc_1)^2\mathrm{k}_2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

$$\frac{de^*}{dc_1} = -\frac{2b(a_0 - bc_0)(\alpha - b\gamma)(a_1 - bc_1)k_1k_2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

$$\frac{dq^*}{dk_2} = -\frac{(a_0 - bc_0)(\alpha - b\gamma)^2(a_1 - bc_1)k_1}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

$$\frac{dq^*}{d\gamma} = -\frac{2b(a_0 - bc_0)(\alpha - b\gamma)(a_1 - bc_1)k_1k_2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

Appendix-2

$$\frac{dD^*}{dk_1} = -\frac{2b(a_0 - bc_0)(a_1 - bc_1)^2{k_2}^2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

$$\frac{dD^*}{dc_1} = -\frac{4b^2(a_0 - bc_0)(a_1 - bc_1)k_1{k_2}^2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

$$\frac{dD^*}{dk_2} = -\frac{2b(a_0 - bc_0)(\alpha - b\gamma)^2{k_1}^2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

$$\frac{dD^*}{d\gamma} = -\frac{4b^2(a_0 - bc_0)(\alpha - b\gamma){k_1}^2k_2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

$$\frac{d{\pi_m}^*}{dk_1} = -\frac{(a_0 - bc_0)^2(a_1 - bc_1)^2{k_2}^2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$
$$\frac{d{\pi_m}^*}{dc_1} = -\frac{2b(a_0 - bc_0)^2(a_1 - bc_1)k_1{k_2}^2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$
$$\frac{d{\pi_m}^*}{dk_2} = -\frac{(a_0 - bc_0)^2(\alpha - b\gamma)^2{k_1}^2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$
$$\frac{d{\pi_m}^*}{d\gamma} = -\frac{2b(a_0 - bc_0)^2(\alpha - b\gamma){k_1}^2k_2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^2} < 0$$

$$\frac{d{\pi_r}^*}{dk_1} = -\frac{8b(a_0 - bc_0)^2(a_1 - bc_1)^2k_1{k_2}^3}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^3} < 0$$
$$\frac{d{\pi_r}^*}{dc_1} = -\frac{16b^2(a_0 - bc_0)^2(a_1 - bc_1){k_1}^2{k_2}^3}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^3} < 0$$
$$\frac{d{\pi_r}^*}{dk_2} = -\frac{8b(a_0 - bc_0)^2(\alpha - b\gamma)^2{k_1}^3k_2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^3} < 0$$
$$\frac{d{\pi_r}^*}{d\gamma} = -\frac{16b^2(a_0 - bc_0)^2(\alpha - b\gamma){k_1}^3{k_2}^2}{[2bk_1(4k_2 + \alpha\gamma) + 2a_1bc_1k_2 - b^2({c_1}^2k_2 + k_1\gamma^2) - a_1^2k_2 - k_1\alpha^2]^3} < 0$$