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IFAC PapersOnLine 55-10 (2022) 1711–1715

Optimal sustainability efforts and pricing policies in a two-echelon supply chain

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Abstract: Stakeholders such as governments, NGOs and customers have made businesses to consider sustainable practices in their operations. Achieving sustainability goals, such as for e.g. carbon emissions reduction often requires coordinated efforts between firms across different echelons in supply chains. This paper aims to study this issue of sustainability efforts by firms in a two-echelon supply chain where pricing decisions are also in mix along with emission reduction policy decisions. We consider a channel in which a manufacturer sells through a retailer where retailer is the dominant firm. Both the firms can put efforts to reduce their respective emission levels. We model a Stackelberg game where retailer as the leader determines its retail price (margin) and its emission reduction efforts and the manufacturer responds by determining its wholesale price and its emission reduction effort. The consumer demand is sensitive to retail price as well as total supply chain wide emissions. We also solve the problem of a centralized decision maker which serves as a benchmark solution. We obtain optimal equilibrium policies and obtain useful managerial insights both through analytical as well as numerical means including the sensitivity of optimal decision variables w.r.t. various exogenous model parameters. We find that in the centralized channel the overall sustainability efforts are higher and in addition the consumers also pay a lower retail price in the centralized channel compared to a decentralized one.

Keywords: Sustainable supply chain management, supply chain management, Stackelberg game, game theory, pricing

1. INTRODUCTION

Increasing pressures from governments, customers and non-profit organizations have made firms to put in greater efforts to strive for sustainability in their supply chains (Seuring and Müller, 2008, Carter and Easton, 2011, Gold et al., 2010, Klassen and Vachon, 2006). Sustainability cannot be achieved without strong collaboration between supply chain partners towards sustainable activities. Many firms have started to work with their suppliers and customers in the whole supply chain towards this objective. There are examples such as Walmart, Avon, Safeway and Target which have re-structured their relationship with their suppliers. In this partnership, suppliers are responsible for sustainable innovation and obtaining environmental standards. Target started collaboration with its suppliers to reduce total supply chain carbon emission by 30% by 2030 with respect to the 2017 emission level (Target, 2019). It is challenging to find a win-win situation for all the participants towards the sustainable developments in the supply chains and therefore it is important to understand the factors which may incentivize the firms in a supply chain to invest in reducing their emissions. In line with the Paris Agreement, there is a target to be climate neutral by 2050 which means establishment of an economy with net zero emissions (European-Commission 2021). For instance, the UK government has considered Emissions Trading Scheme (ETS) to reduce emissions. This scheme is based on cap-and-trade principle which contributes to Net Zero emissions target by 2050 (BEIS 2021). These types of governmental regulations and schemes will assist in transition for businesses to reduce their emissions. However, achieving net zero emissions will require supply chain wide efforts by firms along with effective collaboration between firms at different echelons.

This motivates us to explore incentives behind different firms' actions to reduce supply chain wide carbon emissions. We consider a two-echelon supply chain consisting of a manufacturer and a retailer where the retailer is the dominating firm in the supply chain. We develop a game-theoretic model where both members put efforts to reduce their emissions while trying to maximize their profits. We look to address the following research questions:

1) What are the optimal pricing and emission reduction strategies of the two firms in the supply chain and how do these depend on various exogenous model parameters?

2) How do the optimal price and the overall emission levels compare to a benchmark case of a centralized supply chain?

10.1016/j.ifacol.2022.09.644

3) What are the incentives of different firms towards reducing the emission levels?

2. SUMMARY OF BACKGROUND LITERATURE

While our work is related to the larger stream of literature in sustainable supply chain management, in this section we focus on papers on game-theoretic models in sustainable supply chain management. Table 1 summarizes such models and highlights key differences along between our paper and these existing models along with our contribution. To summarize, to the best of our knowledge, except for Xia et al. (2021), this is the only work that considers the following important and relevant features in game theoretic model for sustainable supply chain management: i) sustainability efforts by both manufacturer and retailer, ii) a retailer led game structure where the retailer is the dominating firm in the supply chain, and iii) where prices are also included as decision variables for both the players (wholesale prices for the manufacturer and retail price for the retailer). One key difference between this paper and Xia et al. (2021) is that we also consider government policy in terms of carbon taxation on the emissions level whereas Xia et al. (2021) do not consider that. Furthermore, in an extension of this work, we focus on collaboration between two firms in sustainability whereas the focus of Xia et al. (2021) is on cross-ownership between two firms in general.

Table 1. An overview of related literature.

Papers	Game Structure*	Effort in a two-echelon supply chain by		Pricing decisions
		Manufacturer	Retailer	
(Xu, Chen, and Bai 2016)	RS		√	√
(Bai, Chen, and Xu 2017)	MS		√	√
(Dai, Zhang, and Tang 2017; Ghosh and Shah 2015; Xu et al. 2017; Yuyin and Jinxi 2018; Wang, Brownlee, and Wu 2020)	MS	√		√
(Yang and Xiao 2017; Chen, Wang, & Chan 2017)	RS MS VN	√		√
(Swami and Shah 2013)	MS	√	√	√
(Xia, Zhi, and Wang 2021)	MS RS	√	√	√
(Yenipazarli 2016)	RS	√		√
(Taleizadeh, Alizadeh-Basban, and Sarker 2018; Wang, Zhao, and He 2016; Heydari, Govindan, and Basiri 2020)	RS	√		√
(Sang 2019)	RS MS VN	√		√
This paper	RS	√	√	√

* RS: Retailer Stackelberg, ** MS: Manufacturer Stackelberg, and ***VN: Vertical Nash

3. MODEL DEVELOPMENT, ANALYSIS, AND RESULTS

We consider a two-echelon supply chain consisting of an upstream manufacturer who sells products to a downstream retailer, where the retailer has greater bargaining power. Both firms put efforts to reduce their carbon emissions and make decisions to maximize their own profits. Table 2 denotes the relevant notation used in this paper.

Table 2. Notation.

Notation	Description
p	Unit retail price of the retailer
c	Unit production cost of the manufacturer
w	Unit wholesale price of the manufacturer
m	Unit margin of the retailer
e_{m0}	Initial total carbon emission of the manufacturer
u_m	Manufacturer greening effort level, considered to be equal to the reduction in manufacturer emission. Thus, final emission level is: $e_{m1} = e_{m0} - u_m$. Where $u_m, e_{m1} \geq 0$
e_{r0}	Initial total carbon emission of the retailer
u_r	Retailer greening effort level, considered to be equal to the reduction in retailer emission. Thus,

	final emission level is: $e_{r1} = e_{r0} - u_r$. Where $u_r, e_{r1} \geq 0$
T_m	Manufacturer cost of greening effort
t_m	Manufacturer greening effort cost coefficient
T_r	Retailer cost of greening effort
t_r	Retailer greening effort cost coefficient
σ	Carbon emission tax coefficient
α	Baseline market demand constant
β	Sensitivity of the customer demand with respect to the price, $\beta \geq 0$
γ	Sensitivity of the customer demand with respect to the total supply chain greening effort, $\gamma \geq 0$
c	Refers to a Centralised channel when used as a subscript/superscript
d	Refers to a Decentralised channel when used as a subscript/superscript
m	Refers to the Manufacturer when used as a subscript/superscript
r	Refers to the Retailer when used as a subscript/superscript
sc	Refers to the overall Supply Chain when used as a subscript/superscript

Furthermore, we include the following features/assumptions in our model.

i) Demand is decreasing in retail price (p) and increasing in total sc greening effort ($u_m + u_r$). Therefore, Demand = $D = \alpha - \beta p + \gamma(u_m + u_r)$. See, for e.g., Yenipazarli (2016), Ghosh and Shah (2015) and Swami and Shah (2013).

ii) The cost of effort is proportional to the square of the effort, and therefore accounts for the diminishing marginal returns from investments in sustainability efforts of the two firms. See, for e.g., Swami and Shah (2013), Ghosh and Shah (2015) and Liu, Anderson, and Cruz (2012). It means that: $T_m = t_m u_m^2$ and $T_r = t_r u_r^2$.

iii) Carbon tax that each firm has to pay is proportional to the emission level. Hence: $Tax_m = \sigma(e_{m0} - u_m)$ and $Tax_r = \sigma(e_{r0} - u_r)$.

iv) Without any loss of generality, we assume that the unit manufacturing cost at the manufacturer's end (c) is zero. The model can be easily modified to consider a non-zero-unit manufacturing cost but that will not have an impact on the insights that we attempt to obtain.

3.1 Centralized channel

Equation (1) represents optimization problem of a centralized decision maker who determines optimal retail price and greening efforts to maximise total supply chain profit.

$$\max_{p,u_m,u_r} [\pi_{sc}(p, u_m, u_r)] \text{ where} \tag{1}$$

$$\pi_{sc}(p, u_m, u_r) = (p - c)\big(\alpha - \beta p + \gamma(u_m + u_r)\big) - t_m u_m^2 - t_r u_r^2 - \sigma(e_{m0} - u_m) - \sigma(e_{r0} - u_r)$$

The optimal results of retail price, manufacturer greening effort, and retailer greening effort are shown in Table 3.

Table 3. Equilibrium results of centralised channel

Model	Decision Variables	Optimal Results
Centralized	p^c	$\frac{\sigma\gamma(t_m + t_r) + 2\alpha t_m t_r}{\gamma^2(-t_m - t_r) + 4\beta t_m t_r}$
	u_m^c	$\frac{\alpha\gamma t_r + 2\beta\sigma t_r}{\gamma^2(-t_m - t_r) + 4\beta t_m t_r}$
	u_r^c	$\frac{\alpha\gamma t_m + 2\beta\sigma t_m}{\gamma^2(-t_m - t_r) + 4\beta t_m t_r}$

The results in Table 3 are obtained by simply applying first-order conditions in maximization w.r.t. the decision variables. The second order conditions can be verified as the corresponding Hessian matrix can be shown to be negative-definite

3.2 Decentralized channel

Here, the retailer being the leader, first decides its retail margin ($p^d - w^d$) and its greening effort (u_r^d) to maximize its profit. The manufacturer, in response, determines the wholesale price (w^d) and its greening effort (u_m^d) given the retailer's optimal decisions. Equation (2) expresses manufacturer's profit function.

$$\max_{w,u_m} [\pi_m(w, u_m)] \text{ where} \tag{2}$$

$$\pi_m(w, u_m) = w[\alpha - \beta(m + w) + \gamma(u_m + u_r)] - t_m u_m^2 - \sigma(e_{m0} - u_m)$$

Equation (3) shows retailer's profit function.

$$\max_{m,u_r} [\pi_r(m, u_r)] \text{ where} \tag{3}$$

$$\pi_r(m, u_r) = m[\alpha - \beta(m + w) + \gamma(u_m + u_r)] - t_r u_r^2 - \sigma(e_{r0} - u_r)$$

The optimal results of the decentralized channel are listed in Table . We use the standard backward induction approach to solve this game.

Table 4. Equilibrium results of decentralised channel.

Model	Decision Variables	Optimal Results
Decentralized	w^d	$\frac{\sigma\gamma t_m + 2t_m t_r \alpha}{(-2t_r - t_m)\gamma^2 + 8\beta t_m t_r}$
	p^d	$\frac{(2t_r\alpha + \gamma\sigma)(-6\beta t_m + \gamma^2)}{2\beta(-8\beta t_m t_r + \gamma^2 t_m + 2\gamma^2 t_r)}$
	u_m^d	$\frac{2\alpha\gamma t_r + \gamma^2\sigma}{(-2t_m - 4t_r)\gamma^2 + 16\beta t_m t_r}$
	u_r^d	$\frac{-\alpha\gamma t_m - 4\beta\sigma t_m + \gamma^2\sigma}{-8\beta t_m t_r + \gamma^2 t_m + 2\gamma^2 t_r}$

To obtain the results in Table 4 we first solve the followe, i.e., manufacturer's problem to obtain its optimal decisions given retailer's choice of its margin and sustainability effort. We then use retailer's optimal response to solve for the retailer's optimization problem.

3.3 Key results and findings.

Some key results and insights from our analysis are discussed below.

Corollary 1: sensitivity of emission reduction efforts:

u_m^c, u_m^d, u_r^c and u_r^d are increasing in γ and σ; and decreasing in β, t_m and t_r.

Corollary 2: sensitivity of retail prices

p^c and p^d are increasing function in γ and σ; and decreasing in β, t_m and t_r.

The results in Corollary 1 and 2 can be obtained by simply analyzing the signs first derivative of optimal decision variables w.r.t. different model parameters

Corollaries 1 and 2 indicate that when customers are more conscious towards sustainability, or when the government's carbon taxation rate is higher, the firms put a greater greening effort. However, the firms also tend to pass on the burden of greater carbon reduction to customers and the customers pay a higher retail price. On the other hand, the firms' greening efforts as well as retail prices are lower when customers are more sensitive to price or when implementing green efforts is more costly for the firms.

Numerical Analysis:

We also conducted numerical analysis to obtain further useful managerial insights. We conducted numerical analysis for a wide set of model parameters and summarize here some of the key observations which may provide useful insights for firms as well as policy makers. These insights are summarized below. Quite expectedly, we find that retail price in a decentralized channel is higher than that in a centralized channel. In addition, both the firms' greening efforts are higher in a centralized channel as compared to a decentralized one. Thus, a centralized channel not only results in lower emissions level but also lower price for the consumers. Finally, we find that profits of both the firms are increasing in γ and σ; and decreasing in β, t_m and t_r.

4. EXTENSIONS AND FURTHER RESEARCH WORK

In an extension of the work presented in this paper, we consider a model in which pricing are not decision variables and firms focus only on their optimal emission reduction policies and obtain some interesting insights. Furthermore, we investigate the issue of collaboration between the two firms and specifically model a cost sharing arrangement between the two firms towards reduction of total supply chain emissions.

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