GREEN PRODUCT AND PROCESS DESIGN IN SUPPLY CHAINS

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ABSTRACT

In this paper, we build economic models to study how supply chain choices interact with a firm's green products and process design strategies. First, our results indicate that the distortion from a non-coordinated supply chain (the double marginalization effect) has nonintuitive impact on the degree of product "greenness" the firm may provide. We also study impact of green process and product strategies on product green attributes ("greenness") under different supply chain structures including centralized and decentralized competing supply chains. The results show that the horizontal competition normally increases the product greenness attributes under both the product and the process innovation approach. The insight from this paper can help not only a manufacturer of green product, but also the regulator to build a more sustainable supply chain strategy in this era of economic recovery.

Keywords: Green Product Design, Green Process Design, Sustainable Supply Chain Management

INTRODUCTION

Sustainable supply chain management has received more and more attention during the last ten years. There are large body of literature in different areas like production and operations management, industrial organization, marketing and consumer behavior, and more recently, supply chain management, which is the area that this paper contributes to. As mentioned in Kleindorfer, Kaylan, and Van Wassenhove (2005), sustainable OM has three main areas including green product and process development, lean and green OM, remanufacturing and closed-loop supply chain. Based on the former literature and discussion of green product and process design under the context of operations, this paper tries to address these issues at a strategic level and under different supply chain settings. Albino, Balice, Dangelico, and Iacobone (2012) argues that firms need to develop their environmental strategy first to support the green product design and green process development. However, these two approaches come with different costs and certainly different consequences on supply chain and consumers. Wong (2012) investigates the impact of green product design and green process innovation on green product competitive advantage and green product success. Wong (2012) argues that under limited resources, green product innovation should be pursued first because green product design exerts a stronger influence on both the competitive advantage and product success than green process innovation. This explains why green product design is more advertised and applied in real business practices, while on the other hand, there are still argument on the impact of green process innovation, for example, the green versus lean argument in Kleindorfer, Kaylan, and Van Wassenhove (2005). Various related studies have been performed on green product design. Sroufe, Curkovic, Montabon, and Melnyk (2000) discusses the timing difference of adopting green product design. Chung and Tsai (2007) provides evidence showing that higher green design activities result in better implementation of development strategies of new products.
and better development performance of new products. Eichner and Pethig (2003) study the impact of pollution taxation on green product design and recycling, and show that the rising tax rates do stimulate recycling and green product design but may have negative impact on operations efficiency and recycling ratio. However, the literature on green strategies under supply chain setting is sparse. Based on the former theoretical and empirical studies, this paper uses economic models to describe and study the adoption of these two green strategies (process approach versus product approach) under different supply chain settings.

THE MODEL

In this section, we present the model with the main results found. The proofs are not included for this version.

Assumptions

Consider a manufacturer and a retailer in a supply chain. The manufacturer designs and produces a product with certain degree of greenness (lower environmental impact), which we denote as a parameter $\alpha$, where $0 \leq \alpha \leq 1$ with higher $\alpha$ represents higher degree of greenness. There are different ways to describe the green attributes of a product supply chain. Chen (2001) uses a quality based model to describe the greenness of a product. Noori and Chen (2003) use different environmental attributes to describe the greenness specifically for biotechnology products. Subramanian, Gupta, and Talbot (2009) model two green attributes: performance attribute (during product consumption or usage) and remanufacturability attribute (post product usage). These different ways to describe green attributes are from either the process or the product view, therefore, in this paper, $\alpha$ is assumed to be the result from the manufacturer's green process and product designs. This green index can affect the manufacturer's fixed costs, which are the results of the manufacturer's choice of supply configuration and manufacturing infrastructure, such as sales channels, facility locations, manufacturing processes, equipments, product design, and specific investment to be able to utilize recycled material and to recycle the product by the end of its life span. $\alpha$ also affects the manufacturer's variable costs (such as transportation and production), which are the results of the manufacturer's choice of recycled material, material that can be recycled, low toxicity material, and/or biodegradable material. Therefore, we model the manufacturer's costs to provide $d$ amount of the product with degree of greenness $\alpha$ as a function that includes both fixed and variable parts. The fixed cost is a convex function in $\alpha$, which reflects the fact that it is increasingly more costly to invest in a more sustainable supply chain infrastructure in order to achieve higher $\alpha$. To keep our results tractable, we use a specific convex function as the fixed cost $f\alpha^2$. The variable cost part is also a convex function in $\alpha$, and again for tractability purpose we use a specific form of: $v\alpha^2$. Therefore, the variable cost becomes higher when the degree of greenness increases.

At the same time, $\alpha$, or the degree of greenness, also has a "green" appeal on the consumer demand. Therefore, in this paper we assume that the manufacturer will be able to credibly signal the degree of greenness to its consumers, and in return, the consumers in general have preference for products that are greener. In this supply chain, we assume that the retailer determines the selling price $p$ for the product. The market demand $d$ is modeled as $d = a - p + b \alpha$, where $a, b > 0$. The constant $a$ indicates the market potential while the coefficient $b$ measures the marginal consumer
demand with the degree of greenness. There are different empirical research (Klein (1990), Chase and Smith (1992)), polls by polling firms (Saad 2006), and private interest groups such as National Geographic Greendex survey provide evidences on this sensitivity parameter \( b \) and a conflicting picture on consumer demand for green products and services. Recent research by Olson (2013) argues that this market sensitivity \( b \) is determined by the comparison among the product's green attributes (for example, green index, environmental index, or emission index) and the product's conventional attributes (like the product durability, reliability, conformance, and other traditional quality attributes). Olson (2013) demonstrates that consumer shows strong preference for green products \((b > 0)\) when tradeoffs between green attributes and conventional attributes are not apparent. Therefore, in this paper, \( b \) is assumed to be based those tradeoffs. For tractability, we further require \( b < 2\sqrt{f} \) to ensure the joint \((b \text{ and } \alpha)\) concavity of the profit function. Similarly we also require \( b < 2\sqrt{v(a-p)} \). The manufacturer determines both the wholesale price \( w \) and the design green index \( \alpha \).

**Two approaches of green strategy**

One approach in a manufacturer's green product strategy starts with the usage of recycled or recyclable material in its product, in which case the cost of providing the greenness is primarily in the form of a variable cost. We call this approach the "product approach" in the green product strategy. Another approach in the manufacturer's green product strategy is to invest upfront in product design, process innovations, and manufacturing infrastructure in order to reduce energy consumption and emission, and to increase recyclability. In this approach that we call "process approach", the cost of providing greenness is primarily in the form of fixed investment. Therefore, To focus our attention to the specific approach of the green product manufacturer, we will study two special cases of our general model: the quadratic variable cost only case for the product approach in the green product strategy, and the quadratic fixed cost only case for the process approach.

**Centralized model**

As a benchmark, we formulate a model in which a centralized supply chain manufactures a green product and sells it directly to the consumers. The profit function of the centralized supply chain with a product approach in its green product strategy is as follows,

\[
\Pi^E_C = (a - p + b\alpha)(p - v\alpha)^2
\]  

(1)

The optimal degree of greenness \( \alpha \) is \( \frac{b}{2v} \), and optimal retail price is \( \frac{a}{2} + \frac{3b^2}{8v} \), and the profit of the centralized supply chain is \( \frac{(b^2 + 4av)^2}{64v^2} \). Similarly, the profit function of the centralized supply chain with a process approach in its green product strategy is as follows,

\[
\Pi^L_C = p(a - p + b\alpha) - f\alpha^2
\]  

(2)

The optimal degree of greenness \( \alpha \) in this case is \( \frac{ab}{4f-b^2} \), and the profit of the centralized supply chain is \( \frac{a^2f}{4f-b^2} \).
Decentralized model with a product approach in green strategy

When the manufacturer adopt a product approach in its green product strategy, it provides a green product by using the recycled or recyclable material in its product. Therefore, $\alpha$ mainly affects the variable production cost and its impact on the fixed cost is negligible. We will ignore the constant fixed cost in our model. In this non-coordinated supply chain, the manufacturer and the retailer engages in a two-stage game. In the first stage of the game, the manufacture decides the degree of greenness $\alpha$ and the whole sale price $w$ with the anticipation of retailer's reaction. After observing the manufacturer's decisions, the retailer will then determine the retail price in the second stage of the game. We have the retailer's profit function as follows (E here is used to represent product approach and L is used for process approach),

$$\Pi^E_R = (a - p + b\alpha)(p - w)$$

(3)

From the above profit function, we can obtain the retailer's response function as $p^* = \frac{a + w + b\alpha}{2}$. The manufacturer's profit function is as follows,

$$\Pi^E_M = (w - v\alpha^2)(a - p^* + b\alpha)$$

(4)

Substituting the response function into the above profit function and solving for the manufacturer's optimal strategy $(w, \alpha)$, we have $w^* = \frac{3b^2 + 4a\alpha}{8v}$ and $\alpha^* = \frac{b}{2v}$. (Due to the length of mathematical proofs, the mathematics in the paper are omitted and will be provided in the Appendix.) Based on these, the retailer's optimal strategy can also be obtained as, $p^* = \frac{7b^2 + 12av}{16v}$. The closed form profit functions under this scenario can be obtained as,

$$\Pi^E_R = \frac{(b^2 + 4av)^2}{256v^2}$$

(5)

$$\Pi^E_M = \frac{(b^2 + 4av)^2}{128v^2}$$

(6)

$$\Pi^E_C = \frac{3(b^2 + 4av)^2}{256v^2}$$

(7)

**Proposition 1** When a manufacturer is in its product approach of green product strategy and the cost of providing the greenness is primarily variable in the degree of greenness, its optimal degree of greenness will not be affected by its supply chain distortion even though the lack of coordination of its supply chain results in less sales and less total profit of the whole supply chain. Instead, the manufacturer's optimal degree of greenness is determined by the ratio of the market appeal of greenness and the marginal variable cost of the greenness $\frac{b}{2v}$.

It is interesting to see that even though the lack of coordination in the supply chain results in less efficiency, the total profit of the decentralized supply chain is only 3/4 of the centralized one, the degree of greenness $\alpha$ that both supply chains provide are identical. Therefore, the double marginalization of decentralized supply chain has no impact on the manufacturer's green product strategy when the manufacturer adopts a product approach of the green product strategy. As expected, the decentralized supply chain has a higher retailer price and lower sales than the centralized one. The
sales difference between the centralized and the decentralized supply chain is $\frac{b^2 + 4aw}{16v}$.

**Decentralized model with process approach of green product strategy**

After the manufacturer adopted recycled or recyclable material in its product design, it may reach a limit for the degree of greenness in its product without significantly affecting the other performance quality. Eventually the manufacturer has to invest in product/process design for breakthrough. For more comprehensive green product strategy that go beyond the use of recycled or recyclable material, the manufacturer also has to invest in the business processes to reduce energy consumption and emissions. The process approach of the green product strategy requests the manufacturer to invest in its product design, manufacturing processes, and other manufacturing infrastructure that will make the product "greener". In a decentralized supply chain, the two-stage game still has the same structure as we discussed in section 2.4. The retailer's profit function can be written as,

$$\Pi_R^L = (a - p + b\alpha)(p - w)$$  \hspace{1cm} (8)

We obtain the same response function as $p^* = \frac{a-w+ba}{2}$. The manufacturer's profit function is,

$$\Pi_M^L = w(a - p^* + b\alpha) - f\alpha^2$$  \hspace{1cm} (9)

Therefore, the manufacturer's optimal decisions can be found as,

$$w^* = \frac{4af}{8f - b^2}$$  \hspace{1cm} (10)

$$\alpha^* = \frac{ab}{8f - b^2}$$  \hspace{1cm} (11)

Further, the retailer's optimal price is set at $p^* = \frac{6af}{8f - b^2}$. With these results, we have the retailer's profit as $\Pi_R^L = \frac{4a^2f^2}{(8f-b^2)^2}$, the manufacturer's profit is $\Pi_M^L = \frac{a^2f}{8f-b^2}$, and the total supply chain profit is $\Pi_C^L = \frac{f(12f-b^2)^2a^2}{(8f-b^2)^2}$.

**Proposition 2** When a manufacturer adopt a process approach of green product strategy and therefore the cost of providing greenness is primarily fixed in the degree of greenness, its incentive to provide greenness is negatively affected by the lack of coordination in its supply chain. As a result, the optimal degree of greenness is reduced by $\frac{4abf}{(8f-b^2)(4f-b^2)}$.

When the manufacturer is in its process approach of green product strategy and it has to invest in the process innovation to increase the degree of greenness, the double marginalization of the decentralized supply chain force the manufacturer to choose a lower degree of greenness $\alpha$. Therefore, it become crucial to have a coordination mechanism in the supply chain in order to alleviate the negative impact on the degree of greenness.

**DECENTRALIZED MODEL WITH COMPETING RETAILERS**

Besides the vertical competition in a supply chain, the following sections focus on the horizontal and vertical competitions. We first study competing retailers under single manufacturer. Assuming
that there are two competing retailers who offer this product to different markets and set their prices separately. The demand functions for these two markets are, \( D_1 = a_1 - p_1 + sp_2 + b_1\alpha \) and \( D_2 = a_2 - p_2 + sp_1 + b_2\alpha \), where \( s \) represents the product substitutability for the two markets. Under the product approach of green product strategy, the retailers' profit functions are \( \Pi^{E}_{RE1} = (a_1 - p_1 + sp_2 + b\alpha) \) and \( \Pi^{E}_{RE2} = (a_2 - p_1 + sp_1 + b\alpha) \). The equilibrium can be found as,

\[
p_1^* = \frac{2a_1 + 4s + 2ab(2 + s) + 2w + sw}{4 - s^2} \\
p_2^* = \frac{2a_2 + 4s + 2ab(2 + s) + 2w + sw}{4 - s^2}
\]

The manufacturer's profit function is,

\[
\Pi^{E}_{EM} = (w - v\alpha^2)(a_1 + a_2 - (1 - s)(p_1 + p_2 + b\alpha))
\]

Proposition 3 When a green product manufacturer provides its product through two competing retailers instead of only one retailer, the optimal degree of greenness will increase as a result of the competition between the two retailers. The amount of increased greenness also increases with the degree of product substitutability.

Therefore, under this scenario, higher \( \alpha \) is observed than the single retailer case.

IMPACT OF SUPPLY CHAIN COMPETITION ON THE OPTIMAL DEGREE OF GREENNESS

To understand the impact of competition on the optimal degree of greenness, we explore the competition between two integrated supply chains in both product and process approach of green strategies and also the competition between two non-coordinated supply chains in the green product strategy. In all the cases explored, we then compare the degree of greenness to a monopolist supply chain. Generally, all these results show that competition will indeed increase the optimal degree of greenness.

First, for two competing vertically integrated supply chain (VISC), their profit functions at product approach are \( \Pi^{E}_{VISCi} = (p_i - v\alpha_i^2)(a_i - p_i + sp_j + b\alpha_i), \) where \( i \in 1,2, j \in 1,2, i \neq j \). For tractability purpose, we solve this problem in two stages, in first stage both VISC's determine their degree of greenness and in second stage both VISC then determine their price. The information is transparent in both stages of the game. Solving the two-stage game in backward induction, our results show that the optimal degree of greenness for each VISC is \( \frac{b}{2v(1-s)^2}\). Compared to the optimal degree of greenness offered by a centralized supply chain in its product approach of green product strategy, it is clear that competition increase the degree of greenness. It is also obvious that the higher of the substitutability between the two products the larger the increase of the degree of greenness. Second, for two competing VISC's, their profit functions under process approach are \( \Pi^{E}_{VISCi} = p_i(a_i - p_i + sp_j + b\alpha_i) - f\alpha_i^2, \) where \( i \in 1,2, j \in 1,2, i \neq j \). Our results show that
the optimal degree of greenness for each VISC is $\frac{ab}{2f(2-s)-b^2}$. Compared with the optimal degree of greenness offered by a centralized supply chain in its process approach of green product strategy, it is clear that competition increase the degree of greenness. It is also obvious that the higher of the substitutability between the two products the larger the increase of the degree of greenness. Now, consider two competing non-coordinated supply chains of green products, each with one manufacturer and one retailer. Both are in their process approach of green strategy and therefore the costs of providing greenness are primarily fixed. Within each supply chain, the decision process is similar to our previous model. Between the two supply chains, the two retailers engage in simultaneous price competition in one consumer market once the two manufacturers made their decisions of wholesale prices and the degree of greenness. The profit functions of the two competing retailers are as follow:

$$\Pi_{R1}^{NCSC} = (p_1 - w_1)(a_1 - p_1 + sp_2 + b\alpha_1)$$ (15)
$$\Pi_{R2}^{NCSC} = (p_2 - w_2)(a_2 - p_2 + sp_1 + b\alpha_2)$$ (16)

The profit functions of the two manufacturers are as follow:

$$\Pi_{w_1}^{NCSC} = w_1(a_1 - p_1 + sp_2 + b\alpha_1) - f\alpha_1^2$$ (17)
$$\Pi_{w_2}^{NCSC} = w_2(a_2 - p_2 + sp_1 + b_2\alpha_2) - f\alpha_2^2$$ (18)

Solving the Nash equilibrium of the two competing retailers for the retail prices, we can go back and solve the two manufacturers' problems and find out the optimal wholesale price and degree of $\alpha$ for each manufacturer. The resulting $\alpha$ is as follows:

$$\alpha_1 = \frac{b(2a_2 f s(3 - s^2) + a_1(-b^2 + f(8 - 3s^2)))}{b^4 + 2b^2 f(3s^2 - 8) + f^2(64 - 84s^2 + 33s^4 - 4s^6)}$$ (19)
$$\alpha_2 = \frac{b(2a_1 f s(3 - s^2) + a_2(-b^2 + f(8 - 3s^2)))}{b^4 + 2b^2 f(3s^2 - 8) + f^2(64 - 84s^2 + 33s^4 - 4s^6)}$$ (20)

**Proposition 4** Competition from another green product supply chain will always increase the degree of greenness offered in the market whether the green product supply chains are vertically integrated or non-coordinated. The amount of the increase as a result of competition is also increasing with the degree of product substitutability.

**FUTURE RESEARCH AND CONCLUSION**

This paper uses economic modeling approach to study the green product and process design problems in the settings of different supply chain structures (including coordinated supply chain, vertical competing supply chain, and horizontal competing supply chains). For both centralized and decentralized models, close forms of the optimal strategies are obtained. From these analytical results, the product greenness can be compared under different scenarios. There are two main observations from these analytical results. First, supply chain distortion from double marginalization effect under product approach does not influence the greenness decisions; while under process approach, this distortion reduces the product greenness design. Second, under different supply chain competition structures, our results indicate that competition increases the green design. These results may help
firms make better choices on aligning their sustainability strategies with their supply chain choices.

There are a few directions that we would like to further explore. First, the joint effect from both green product approach and green process approach should be considered under different supply chain settings to gain insights on the tradeoffs and interactions between these two approaches. Second, under the supply chain competition scenarios, we can certainly relax the assumptions like same substitutability coefficient and same parameter sets for competing supply chains. Third, we have shown the different impacts of decentralization effect on green design under product and process green strategies. A natural extension is to actually provide the coordination mechanism in promoting green design of product and process, which is our on-going research.

REFERENCES


