ABSTRACT

To understand the dynamics of the manufacturer’s effort to reduce the pollution in a supply chain consisting of manufacturer, retailer, and consumers, we analyze four cases according to consumer awareness of the pollution’s harmful effect (environmentally aware versus ignorant) and supply chain strategy (competitive versus cooperative). Applying differential games models, we derive managerial implications: the most significant is that the supply chain strategy becomes irrelevant to reducing the pollution, unless the consumers are environmentally aware or sensitive enough. It highlights the critical role played by the consumer awareness in curbing the pollution in the supply chain. In addition, we find the transfer price and the potential market size are important factors to determine each case’s relative effectiveness, i.e., whether a case is better than the others. Under a regular condition, where the transfer price from the retailer to the manufacturer is sufficiently high, the consumer-aware and competitive case can generate a better outcome in reducing the pollution than those with ignorant consumers. But, the opposite might occur if the transfer price is excessively low, giving the manufacturer little motivation to make an effort to reduce the pollution. For the cooperative supply chain, it is the potential market size that determines whether the consumer-aware case is better than the consumer-ignorant. In fact, it turns out that there is a stronger result, i.e., the feasibility condition enforces that the market is always big enough to make the consumer-aware cooperative case is better than the consumer-ignorant cases. We further discuss managerial as well as policy implications of these analysis outcomes.

KEYWORDS: Consumer awareness, Supply chain coordination strategy, Pollution abatement

INTRODUCTION

These days sustainable supply chain management is an immensely important issue both managerially and economically (Kleindorfer et al., 2005; Krass et al., 2013; Linton et al., 2007; Seuring & Müller, 2008), as the environmental concerns are increasingly becoming central to global economic as well as political arenas. Srivastava (2007) defined green supply chain management by postulating that “Adding the ‘green’ component to supply-chain management involves addressing the influence and relationships between supply-chain management and the natural environment.” There are two underlying forces, which have driven the growing importance of green supply chain management. On the one hand, there is a government regulation, which forces the business to reduce its emission of pollutant. On the other hand,
there is a collective power of consumers, whose purchasing decision can send a strong signal to the business. In this context, we define important questions to ask, i.e., “Which one, supply chain strategy or consumer awareness, is more conducive to reducing the pollution? Is there any relationship between the two in minimizing the pollution emission? Which one, government regulation or consumer awareness, is more powerful in curbing the pollution?” in order to answer these questions, we develop four differential games models, using two dimensions, consumer awareness (aware versus ignorant consumers) and supply chain strategy (competitive versus cooperative). After analyzing these differential games models, we put forth significant managerial implications.

The paper is structured as follows. In the next section, we review relevant literature. Then, we develop four differential games models, according to two dimensions, i.e., supply chain strategy (competitive versus cooperative) and consumer awareness (aware versus ignorant). After solving the differential games models, we postulate theorems. Finally, we discuss the managerial implications of the research outcomes and suggest conclusions.

**LITERATURE REVIEW**

Regarding the environmentally sustainable value chain, a number of studies examined how the regulators could effectively induce greener supply chain through diverse instruments and incentives (Jung et al., 1996; Benchekroun & Long, 1998; Chen & Sheu, 2009; Li, 2013). Milliman & Prince (1989) investigated five regulatory regimes such as direct controls, emission subsidies, emission taxes, free marketable permits and auctions marketable permits and examined which policy would facilitate firms’ technological change in pollution control most. Jung et al. (1996) also evaluated the effectiveness of various regulatory instruments in terms of firms’ incentives to develop and adopt pollution abatement technology. Subramanian et al. (2007) examined how firms’ pollution abatement strategies would vary under a regulator’s decision on the permits for emissions.

More recently, there has been emerging interests in operational and market factors beyond the regulatory policies in inducing firms’ environmental performance, i.e., supply chain strategy and consumer awareness. In reviewing studies in environmentally and socially sustainable operations, Tang & Zhou (2012) also emphasized that the role of environmentally conscious consumers and cooperation within a supply chain deserve further investigation.

In the supply chain strategy, the commonly accepted view is that the cooperative supply chain leads to a higher environmental performance (Handfield et al., 1997; Simpson, 2010; Hollos et al., 2012). Ni et al. (2010) examined the responsibility of contract offering when an upstream supplier invests in activities such as reducing emissions and this investment cost is shared with a downstream manufacturer via a contract. They found that socially responsible or environmental performance is highest in the integrated supply chain where the supplier and the manufacturer jointly maximize the supply chain profit, mainly because the double marginalization problem is eliminated. Klassen & Vachon (2003) empirically showed that upstream or downstream collaboration within a supply chain influenced firm’s environmental investment, based on a sample of Canadian plants. Specifically, they found that increased collaboration in a supply chain resulted in a higher investment in environmental programs.

Consumer’s increasing preference towards environment-friendly products is another important mechanism for firms to reconsider their environmental strategy. Lee (2010) described how consumer’s environmental awareness influenced Esquel, one of the leading suppliers of
premium cotton, to improve its environmental sustainability. Several studies incorporated environmentally conscious consumers explicitly and analyzed its impact on firms’ decisions and environmental performance. Bagnoli & Watts (2003) investigated how firms’ competition for socially responsible or environmentally friendly consumers influenced firm’s decisions. Yalabik & Fairchild (2011) showed that pressures from environment-conscious consumers and regulators both lead to lower emissions as long as the initial emissions are not severe. Also, they found that firms’ environmental competition not only induce lower emissions but also improve the effectiveness of environmental pressures from consumers or regulators. Liu et al. (2012) also examined the impact of consumer’s environmental awareness on the firms with different level of eco-friendly operations and how it changes depending on the level of competition.

Despite the importance of supply chain strategy and consumer’s environmental awareness, however, how the two factors simultaneously affect firm’s environmental performance remains largely unexplored. One notable exception is a study of Zhang et al. (2015). They examined how consumer environmental awareness would influence the order quantity decision and profits in three supply chain scenarios, i.e., a centralized supply chain, a decentralized supply chain and a decentralized supply chain with a return contract. Specifically, they consider two types of products, traditional product and environmental product, which are differentiated in price and environmental quality. Our study is different from their study in two critical aspects. First, we are interested in firm’s environmental investment decision while they assume the exogenously given environmental quality. This feature makes a significant difference since it enables us to directly investigate the impact of supply chain strategy and consumer’s awareness on firm’s environmental behavior. Second, we compare the environmental performance of four cases which are categorized based on supply chain strategy (competitive vs. cooperative) and consumer’s characteristics (environmentally aware vs. ignorant) while they focus on the impact of consumer’s environmental awareness on the order quantity decision and profits in each supply chain.

In examining firm’s emissions abatement effort, Subramanian et al. (2007) distinguished investments toward fixed emission abatement from investments toward per-unit emission abatement. Specifically, they proposed two types of abatement, one for reduction in emissions independent of production volume and another for reduction in emissions per unit production. In a similar vein, Chung et al. (2013) specified two sources of manufacturer’s emissions, one from plant operations independent of production rate and another that is proportional to production rate. Different from many studies examining firm’s abatement of emissions per unit output (e.g., Boucekkine et al., 2011; Krass et al., 2013; Li, 2013), we focus fixed emission from plant operation that proportionally increases with plant capacity (Denholm & Kulcinski, 2004; Meier et al., 2005). Several empirical studies reported that plants with larger capacity had higher emissions and lower environmental performance (e.g., Laplante & Rilstone, 1996; Grant et al., 2002; Gray & Shadbegian, 2004; Ludwig, 2004; Vachon & Klassen, 2006). In practice, Samsung recently reduced fixed emissions through various investment activities at plant level facilities such as optimizing air-conditioner operation, installing high energy-efficient boilers and preventing steam leak (Samsung, 2012).

DIFFERENTIAL GAME MODELS AND ANALYSIS OUTCOME

The setting of our research problem can be described as in Figure 1. The supply chain consists of three primary players, manufacturer, retailer, and consumer. The manufacturer produces and sells its product to the retailer, who in turn sells the product to the end consumer. It is the
manufacturer that emits pollution during the production process, which causes the environment to deteriorate (Klassen, 2001; Chung et al., 2013). The government imposes penalty on the manufacturer for its pollution emission.

Figure 1: A general Context of Sustainable Value Chain

There are two dimensions, i.e., supply chain strategy and consumer awareness level, which define the specific contexts of the supply chain. We consider two different supply chain strategies, competitive versus cooperative. Under the competitive supply chain strategy, each of the two supply chain participants, i.e., manufacturer and retailer, makes its own decision so as to maximize its own profit. On the contrary, under the cooperative supply chain strategy, the two participants are making a decision as if both belong to the same decision-making entity, i.e., they have one objective function combining their profits together. In addition, we consider two types of consumers, one who is aware of and sensitive to the pollution emitted by the manufacturer and the other who is ignorant of and insensitive to that. If the consumer is aware of and sensitive to the pollution emitted by the manufacturer, she will take into account it when making a purchasing decision. That is, the consumer’s demand function is affected by the level of the pollution stock. Using these two dimensions, we develop and analyze four models (Figure 2), ignorant consumer and competitive strategy (Model 1), aware consumer and competitive strategy (Model 2), aware consumer and cooperative supply chain strategy (Model 3), ignorant consumer and cooperative strategy (Model 4). The major variables and parameters in the models are described in Table 1.

Figure 2: Models
Table 1: Definition of Variables and Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ(t)</td>
<td>Cumulative pollution at t</td>
</tr>
<tr>
<td>ν(t)</td>
<td>The level of effort by the manufacturer to reduce the emission of pollutants</td>
</tr>
<tr>
<td>f</td>
<td>Cost parameter associated with the penalty on the cumulative pollution, imposed by the government</td>
</tr>
<tr>
<td>e</td>
<td>Cost parameter associated with the manufacturer’s pollution abatement effort</td>
</tr>
<tr>
<td>U</td>
<td>Manufacturer’s plant capacity</td>
</tr>
<tr>
<td>l</td>
<td>Unit pollutant emission per manufacturing capacity</td>
</tr>
<tr>
<td>p₂(t)</td>
<td>Retail price charged by the retailer at time t</td>
</tr>
<tr>
<td>p₁(t)</td>
<td>Transfer price paid to the manufacturer at time t</td>
</tr>
<tr>
<td>c₁</td>
<td>Cost parameter associated with the deviation from the manufacturing capacity U</td>
</tr>
<tr>
<td>c₂</td>
<td>Cost parameter associated with the retailer’s selling the product</td>
</tr>
<tr>
<td>α</td>
<td>Potential market size</td>
</tr>
<tr>
<td>β</td>
<td>Coefficient in the demand function associated with the sales price; if the sales price is ( p₂(t) ), the potential demand is reduced by ( βp₂(t) )</td>
</tr>
<tr>
<td>γ</td>
<td>Coefficient in the demand function associated with the cumulative pollution; if the cumulative pollution is ( γ(t) ), the potential demand is reduced by ( γy(t) )</td>
</tr>
<tr>
<td>δ</td>
<td>Decay rate of the cumulative pollution</td>
</tr>
<tr>
<td>r</td>
<td>Discount rate</td>
</tr>
<tr>
<td>v_1R</td>
<td>Long-run equilibrium of cumulative pollution in model i, ( i = I, II, III, IV )</td>
</tr>
<tr>
<td>v_2R</td>
<td>Long-run equilibrium of the manufacturer’s pollution abatement effort in model i, ( i = I, II, III, IV )</td>
</tr>
<tr>
<td>p_2R</td>
<td>Long-run equilibrium of the sales price in model i, ( i = I, II, III, IV )</td>
</tr>
<tr>
<td>J, J^m, J^r</td>
<td>Objective function to represent the net profit of a supply chain, a manufacturer, or a retailer throughout the entire planning horizon, i.e., ( t ∈ [0, ∞) )</td>
</tr>
</tbody>
</table>

As the base case, we consider Model 1, where consumers are ignorant of the environmental issues and the supply chain partners adopt the competitive supply chain strategy. First, the retailer’s objective function writes:

\[
\text{Maximize } J^r = \int_0^∞ e^{-rt} [(p_2 - p_1)(α - βp_2) - c_2(α - βp_2)^2]dt \tag{1}
\]

In (1), \((p_2 - p_1)(α - βp_2), p_2 ≥ 0\), is the total net profit for the retailer, where \((p_2 - p_1)\) is the unit profit, sales price minus transfer price paid to the manufacturer, and \((α - βp_2)\) is the demand function, i.e., the consumer’s demand for the retailer’s product is a function of the sales price, \(p_2\), charged by the retailer. Assuming a quadratic cost function, we suggest \(c_2(α - βp_2)^2\) is the total cost required for the retailer to sell \((α - βp_2)\) units.

Similarly, the manufacturer’s objective function writes:

\[
\text{Maximize } J^m = \int_0^∞ e^{-rt} [(p_1 - c)(α - βp_2) - c_1(α - βp_2 - U)^2 - e v^2 - fy^2]dt \tag{2}
\]

The manufacturer’s total net profit is \((p_1 - c)(α - βp_2)\), where \(c\) denotes the unit production cost. In addition to the production cost, a cost incurs in a quadratic pattern as the production amount deviates from the manufacturer’s effective capacity, \(U\): the more the production amount deviates from the effective capacity, the larger the quadratic cost, i.e., \(c_1(α - βp_2 - U)^2\). While manufacturing the product, the manufacturer emits pollutants harmful to the environment: \(y\) is the stock of pollution accumulated by \(t\). The government imposes a penalty on the pollution stock, i.e., \(fy^2\). In order to reduce the government’s penalty, the manufacturer makes an effort to cut its emission of pollutants. The effort level is denoted as \(ν\) and an associated cost incurs in a quadratic way like \(ev^2\).
Both the manufacturer and the retailer maximize their objectives subject to the common constraint:

\[ \dot{y} = \bar{U}(l - v) - \delta y, \quad y(0) = y_0 > 0, \text{ where } 0 \leq v < l. \]  

If the manufacturer doesn’t make any effort to reduce the pollution, it emits pollution as much as \( \bar{U}l \) at \( t \), i.e., the amount of pollution emission is proportional to the manufacturer’s capacity (Gray \& Shadbegian, 2004; Laplante \& Rilstone, 1996; Ludwig, 2004): one unit of capacity emits \( l \) units of pollution. If the manufacturer’s effort level to reduce the pollution is \( v \), one unit of capacity emits only \( (l - v) \) units of pollution. The pollution stock \( y \) decays naturally by \( \delta y \) at \( t \).

Now we have the dynamic evolution of pollution stock as \( \dot{y} = \bar{U}(l - v) - \delta y \).

Model 1:

Retailer’s objective writes:

\[
\text{Maximize } J^r = \int_0^\infty e^{-rt} \left[(p_2 - p_1)(\alpha - \beta p_2) - c_2(\alpha - \beta p_2)^2\right]dt
\]  

Manufacturer’s objective writes:

\[
\text{Maximize } J^m = \int_0^\infty e^{-rt} \left[(p_1 - c)(\alpha - \beta p_2) - c_1(\alpha - \beta p_2 - \bar{U})^2 - ev^2 - fy^2\right]dt
\]

Subject to

\[ \dot{y} = \bar{U}(l - v) - \delta y \]  
\[ y(0) = y_0 > 0, \text{ where } 0 \leq v < l \text{ and } p_2 \geq 0 \]

Now let’s consider Model 2, which is different from Model 1 in one aspect: Model 2 assumes the consumers are aware of and sensitive to the pollution emitted by the manufacturer, whereas Model 1 assumes the consumers are ignorant of and insensitive to the pollution. How can we model the consumer’s awareness? In order to incorporate the consumer’s awareness of the pollution, we change the demand function so that it is now a function of not only the sales price, but also the pollution stock, i.e., \( \alpha - \beta p_2 - \gamma y \), where \( \gamma \) is the demand function’s coefficient associated with the pollution stock (Place a reference here). We provide the decision problems as follows.

Model 2:

Retailer’s objective writes:

\[
\text{Maximize } J^r = \int_0^\infty e^{-rt} \left[(p_2 - p_1)(\alpha - \beta p_2 - \gamma y) - c_2(\alpha - \beta p_2 - \gamma y)^2\right]dt
\]

Manufacturer’s objective writes:

\[
\text{Maximize } J^m = \int_0^\infty e^{-rt} \left[(p_1 - c)(\alpha - \beta p_2 - \gamma y) - c_1(\alpha - \beta p_2 - \gamma y - \bar{U})^2 - ev^2 - fy^2\right]dt
\]

Subject to

\[ \dot{y} = \bar{U}(l - v) - \delta y \]  
\[ y(0) = y_0 > 0, \text{ where } 0 \leq v < l \text{ and } p_2 \geq 0 \]
Model 3 is different from Model 2 in that the manufacturer and the retailer coordinate with each other closely as if they were a single company, i.e., it is the cooperative supply chain strategy. Now there is only one objective function to be maximized by the integrated decision-maker combing the manufacturer and the retailer. The objective function for the cooperative supply chain strategy writes:

\[ J = \int_{0}^{\infty} e^{-rt} [(p_2 - c)(\alpha - \beta p_2 - gy) - c_1(\alpha - \beta p_2 - gy - \bar{U})^2 - ev^2 - fy^2 - c_2(\alpha - \beta p_2 - gy)^2] dt \]

which is the combination of (8) and (9) after canceling out \( p_1 \).

**Model 3:**

Maximize

\[ J = \int_{0}^{\infty} e^{-rt} [(p_2 - c)(\alpha - \beta p_2 - gy) - c_1(\alpha - \beta p_2 - gy - \bar{U})^2 - ev^2 - fy^2 - c_2(\alpha - \beta p_2 - gy)^2] dt \]  

Subject to

\[ \dot{y} = \bar{U}(l - v) - \delta y \]  
\[ y(0) = y_0 > 0, \text{ where } 0 \leq v < l \text{ and } p_2 \geq 0 \]

Finally, Model 4 is different from Model 3 in that the consumers are ignorant of and insensitive to the manufacturer’s pollution stock. Therefore, the demand function is now independent of the pollution stock, i.e., now demand function is \((\alpha - \beta p_2)\), instead of \((\alpha - \beta p_2 - gy)\).

**Model 4:**

Maximize

\[ J = \int_{0}^{\infty} e^{-rt} [(p_2 - c)(\alpha - \beta p_2) - c_1(\alpha - \beta p_2 - \bar{U})^2 - ev^2 - fy^2 - c_2(\alpha - \beta p_2)^2] dt \]  

Subject to

\[ \dot{y} = \bar{U}(l - v) - \delta y \]  
\[ y(0) = y_0 > 0, \text{ where } 0 \leq v < l \text{ and } p_2 \geq 0 \]

We present the detailed solution procedure for Model 2 in Appendix A: note that the solutions for other models are similar with that for Model 2. We summarize the analysis results of the long-term equilibrium for the four models (Table 2).

<table>
<thead>
<tr>
<th>Model</th>
<th>Variable</th>
<th>Long-run equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>( v_{LR}^t )</td>
<td>( -\frac{\bar{U}}{2e} K_{11} )</td>
</tr>
<tr>
<td></td>
<td>( y_{LR}^t )</td>
<td>( -\frac{1}{2f} K_{11} (r + \delta) )</td>
</tr>
<tr>
<td></td>
<td>( p_{2LR}^t )</td>
<td>( \frac{\alpha(1 + 2\beta c_2) + \beta p_1}{2\beta(1 + \beta c_2)} )</td>
</tr>
</tbody>
</table>

Table 2: Summary of Long-term Equilibrium Solutions
### THEOREMS

Based on the analysis of the differential games models, we develop theorems for the long-term equilibrium.

**Theorem 1** At the long-term equilibrium, the manufacturer’s effort to reduce its pollution $(v)$ and the accumulated pollution $(y)$ are identical for Model 1 and Model 4. That is, $v^l = v^{IV}$ and $y^l = y^{IV}$.

**Proof** It is obvious from the analysis above that $K_{11} = K_{41}$ and $m_{12} = m_{42}$ holds, which leads to $A_{12} = A_{42}$. Therefore, $v^l = v^{IV}$ and $y^l = y^{IV}$ holds.

Theorem 1 implies that when the consumers are ignorant of and insensitive to the manufacturer’s pollution emission, whether the supply chain strategy is cooperative or competitive does not make any difference to the manufacturer’s effort to reduce pollution and the resultant accumulated pollution level.

**Theorem 2** There exists a transfer price

$$
\tilde{p}_1 = \frac{(fU^2 + e\delta(r + \delta)\gamma y \bar{u}c_2(r + \delta))}{(1 + \beta c_1 + \beta c_2)\gamma y \bar{u}c_2(r + \delta)}
$$

such that $y^l_{LR} < y^l_{LR} = y^{IV}_{LR}$ and $v^{II}_{LR} = v^{IV}_{LR}$ if $p_1 > \tilde{p}_1$. 

**Proof** See Appendix B.
Theorem 2 examines the pollution dynamics of consumer-aware competitive supply chain, according to the transfer price. In the competitive supply chain, how to set a transfer price is an important mechanism to coordinate various decisions of the manufacturer and the retailer within a supply chain (e.g., Bernstein & Kök, 2009; Gerchak & Wang, 2004; Ni et al., 2010; Wang et al., 2013).

As rearranging (18) yields \( \bar{p}_1 = \left( \frac{1 + \beta c_2}{1 + \beta c_1 + \beta c_2} \right) c - \left( \frac{2 \bar{U}(1 + \beta c_2) - \alpha}{1 + \beta c_1 + \beta c_2} \right) c_1 - \frac{\text{el} \bar{U} c_1 (r + \delta)}{(1 + \beta c_1 + \beta c_2)(f \bar{U}^2 + e \delta (r + \delta))} \), we infer that \( \bar{p}_1 \) is less than the unit production cost \( c \) when \( \bar{U} \) is large compared with other parameters. Consequently, \( p_1 > \bar{p}_1 \) holds given sufficiently large \( \bar{U} \) since it is reasonable to assume that the manufacturer would charge transfer price \( p_1 \) to the retailer that is higher than its unit production cost \( c \). Therefore, we infer that when the capacity is relatively large, the long-term cumulative pollution is the same for Model 1 and Model 4, which is larger than that of Model 2, the consumer-aware competitive supply chain strategy. Similarly, we infer that, when the capacity is relatively large, the manufacturer makes more effort to reduce pollution when the consumers are aware of and sensitive to the pollution stock and the supply chain strategy is competitive than when the consumers are ignorant to the pollution.

**Theorem 3** There exists a market potential level \( \bar{\alpha} = \frac{\text{el} \bar{U} (r + \delta)}{[f \bar{U}^2 + e \delta (r + \delta)]} - \beta (2 c_1 \bar{U} - c) \) such that \( y_{LR}^{III} < y_{LR}^{IV} \) and \( v_{LR}^{III} = v_{LR}^{IV} \), if \( \alpha > \bar{\alpha} \).

**Proof** See Appendix B.

Theorem 3 investigates the consumer-aware cooperative supply chain in terms of pollution emission, according to the potential market size. The potential market size directly influences the payoff in the supply chain, thus having a huge impact on the decisions including optimal emission and abatement of the supply chain (e.g., Subramanian et al. 2007; Yalabik & Fairchild, 2011).

From the long-term equilibrium derived in Table 2, we also reveal that the long-term demand in the Model 3 remains positive if and only if \( \alpha > \frac{\text{el} \bar{U} (r + \delta)}{[f \bar{U}^2 + e \delta (r + \delta)]} - \beta (2 c_1 \bar{U} - c) = \bar{\alpha} \). Therefore, we infer that in general \( \alpha > \bar{\alpha} \) holds and the long-term cumulative pollution is the same for Model 1 and Model 4, which is larger than that of Model 3, the consumer-aware cooperative supply chain strategy. Similarly, we infer that, under a normal situation, the manufacturer makes more effort to reduce pollution when the consumers are aware of and sensitive to the pollution stock and the supply chain strategy is cooperative than when the consumers are ignorant to the pollution.

**Theorem 4** It holds that \( \frac{\partial y_{LR}^i}{\partial f} < 0 \) and \( \frac{\partial v_{LR}^i}{\partial f} > 0 \), where \( i = I, II, III, IV \).

**Proof** See Appendix B.

Theorem 4 implies that as the government's penalty on the manufacturer's pollution stock increases, the manufacturer makes more effort to reduce the pollution and therefore the pollution stock decreases. Another route from the government's penalty to the reduction of the pollution stock is more direct, i.e., the government's penalty directly affects the manufacturer's profit function.
DISCUSSION AND CONCLUSION

We elaborate on each of the theorems. Theorem 1 highlights the importance of consumer awareness in reducing the pollution emitted by the manufacturer. It is well known that whether the supply chain participants are competing or cooperating with each other affects the consequences of supply chain strategy to a great extent. However, our analysis strongly indicates that unless the consumers are aware of and sensitive to the pollution, i.e., taking into account the pollution when making their purchasing decision, there is no difference between the two supply chain strategies in influencing the manufacturer to reduce its emission of pollutant.

Theorem 2 puts forth that a sufficiently large transfer price from the retailer to the manufacturer ensures that the consumer-aware competitive case is better than the consumer-ignorant cases in reducing the pollution. It also implies that if the transfer price is excessively low, it gives the manufacturer little incentive to make an effort to reduce the pollution, leading to less investment in pollution abatement effort and therefore more accumulated pollution stock.

Theorem 3 shows that the consumer-aware cooperative case is better than the consumer-ignorant cases as long as the potential market size is sufficiently large. By proving that such a condition should hold in order for the long-term demand to be positive, it actually confirms that the consumer-aware cooperative case is always better than the consumer-ignorant ones.

Finally, theorem 4 clearly demonstrates that the government penalty is effective for each of the four cases, implying that when executed properly, the government penalty can play an important and effective role in curbing the environmental degradation due to the pollutant emission in the supply chain.

Our research offers significant economic as well as managerial insights. First of all, theorem 1 sheds light on understanding the essential role played by the consumers in controlling the pollution in a supply chain. It seems insightful since it is known in the literature that a cooperative supply chain performs better than a competitive supply chain or at least the literature points out that the two supply chain strategies, i.e., competitive and cooperative, generate very different outcomes in most cases.

It seems also insightful that the transfer price determines whether the consumer-aware competitive case performs better in reducing the pollution than the consumer-ignorant cases. We conjecture in most situations, the transfer price is high enough to make the consumer-aware competitive case perform better than the consumer-ignorant cases. Nevertheless, it is not impossible for the consumer-ignorant cases to perform better than the consumer-aware competitive case if the transfer price is excessively low and thus the manufacturer has little motivation to make an effort to reduce the pollution. For the consumer-aware cooperative case, the analysis result is much stronger. Although the analysis shows that the potential market size determines whether the consumer-aware cooperative case performs better than the consumer-ignorant cases, it runs out that in order to have a feasible solution, i.e., under all the possible realistic situations, the consumer-aware cooperative case always performs better in curbing the pollution than the consumer-ignorant cases.

Finally, it is intriguing to note that the government penalty always forces the firm to increase its investment in pollution abatement and thus to reduce the accumulated pollution stock, regardless of whether the supply chain strategy is competitive or cooperative and also whether the consumers are aware or ignorant. In this light, the government policy seems to be an
effective tool to control the pollution. Nevertheless, this observation does not necessarily mean that the government penalty is a tool more effective than the consumer’s environmental awareness. In fact, it can be a good topic for future research.

We believe our research helps both government policy makers and managers understand the complicated dynamics among critical factors related with consumers and supply chain strategies so as for them to make a decision to control the pollution more effectively.

APPENDIX A

Analysis for Model 2

We present the solution procedure for Model 2 in detail and omit the others, since they are similar with that for Model 2. Recall Model 2:

Maximize $J^r = \int_0^\infty e^{-rt} [(p_2 - p_1)(\alpha - \beta p_2 - \gamma y) - c_2(\alpha - \beta p_2 - \gamma y)^2] dt$

Maximize $J^m = \int_0^\infty e^{-rt} [(p_1 - c)(\alpha - \beta p_2 - \gamma y) - c_1(\alpha - \beta p_2 - \gamma y - \bar{U})^2 - ev^2 - fy^2] dt$

Subject to

$$y = \bar{U}(1-v) - \delta y$$

$$y(0) = y_0 > 0$$, where $0 \leq v < 1$ and $p_2 \geq 0$

The Hamiltonian for the manufacturer’s problem is

$$H^m = (p_1 - c)(\alpha - \beta p_2 - \gamma y) - c_1(\alpha - \beta p_2 - \gamma y - \bar{U})^2 - ev^2 - fy^2 + \lambda_1[\bar{U}(1-v) - \delta y] \quad (A.1)$$

Assuming interior solutions, necessary conditions for optimality lead to

$$v = -\frac{\lambda_1\bar{U}}{2e} \quad (A.2)$$

$$p_1 = \begin{cases} 
0 & \text{if } \alpha - \beta p_2 - \gamma y \leq 0 \\
M & \text{if } \alpha - \beta p_2 - \gamma y > 0 
\end{cases} \quad (A.3)$$

Optimality condition of $p_1$ implies that $p_1^*$ is a bang-bang policy, with the possibility of singular control whenever $\alpha - \beta p_2 - \gamma y = 0$ holds. Note that $p_1 = 0$ can be excluded when $\alpha - \beta p_2 - \gamma y$, the market demand, is nonnegative. If the market demand is zero, we may assign $p_1$ an arbitrary value (e.g., M) because $p_1$ is indeterminate and the choice of $p_1$ does not affect the Hamiltonian. Furthermore, optimal $p_1$ is M for any positive market demand. Therefore, we can expect that the manufacturer always sets his maximum price at M (upper bound of $p_1$) as long as the market demand remains nonnegative. (see Jørgensen 1986)

The Hamiltonian for the retailer’s problem is

$$H^r = (p_2 - p_1)(\alpha - \beta p_2 - \gamma y) - c_2(\alpha - \beta p_2 - \gamma y)^2 + \lambda_2[\bar{U}(1-v) - \delta y] \quad (A.4)$$

Assuming interior solutions, a necessary condition for optimality yields

$$p_2 = \frac{(1 + 2\beta c_2)(\alpha - \gamma y) + \beta p_1}{2\beta(1 + \beta c_2)} \quad (A.5)$$

The solutions that satisfy the necessary conditions are optimal. The objective function of the manufacturer is concave in $(v, p_1)$ and the objective function of retailer is concave in $p_2$. All constraints are linear in $(v, p_1, p_2)$. 
Costate equations are, using (A.5),
\[
\dot{\lambda}_1 = (r + \delta)\lambda_1 + \left(\frac{\gamma^2c_1}{1 + \beta c_2} + 2f\right)y + \gamma(p_1 - c) - 2\gamma c_1(\alpha - \bar{U}) + \frac{\gamma c_1[\alpha(1 + 2\beta c_2) + \beta p_1]}{(1 + \beta c_2)} \tag{A.6}
\]
\[
\dot{\lambda}_2 = (r + \delta)\lambda_2 + \left[2\gamma^2 c_2 - \frac{\gamma^2(1 + 2\beta c_2)^2}{2(1 + \beta c_2)}\right]y + \frac{\gamma(1 + 2\beta c_2)[\alpha(1 + 2\beta c_2) + \beta p_1]}{2\beta(1 + \beta c_2)} - \gamma(p_1 + 2\alpha c_2) \tag{A.7}
\]
Using (10) and (A.2) yields \(\lambda_1 = \frac{2e}{\bar{U}^2} (\dot{y} + \delta y - \bar{U}l)\). Therefore, after rearranging, (A.6) becomes
\[
\dot{y} - r \dot{y} - \left[\delta(r + \delta) + \frac{\bar{U}^2}{2e} \left(\frac{\gamma^2c_1}{1 + \beta c_2} + 2f\right)\right]y = \frac{\bar{U}^2}{2e} \left[\gamma(p_1 - c) - 2\gamma c_1(\alpha - \bar{U}) + \frac{\gamma c_1[\alpha(1 + 2\beta c_2) + \beta p_1]}{(1 + \beta c_2)}\right] - (r + \delta)\bar{U}l \tag{A.8}
\]
Corresponding homogenous equation is
\[
\dot{y} - r \dot{y} - \left[\delta(r + \delta) + \frac{\bar{U}^2}{2e} \left(\frac{\gamma^2c_1}{1 + \beta c_2} + 2f\right)\right]y = 0 \]
and the auxiliary equation is
\[
m_2^2 - rm_2 - \left[\delta(r + \delta) + \frac{\bar{U}^2}{2e} \left(\frac{\gamma^2c_1}{1 + \beta c_2} + 2f\right)\right] = 0, \text{ where the two roots are}
\]
\[
m_{21} = \frac{\bar{U}^2 + \sqrt{\bar{U}^4 + 4\left[\delta(r + \delta) + \frac{\bar{U}^2}{2e} \left(\frac{\gamma^2c_1}{1 + \beta c_2} + 2f\right)\right]}}{2} > 0 \quad m_{22} = \frac{\bar{U}^2 - \sqrt{\bar{U}^4 + 4\left[\delta(r + \delta) + \frac{\bar{U}^2}{2e} \left(\frac{\gamma^2c_1}{1 + \beta c_2} + 2f\right)\right]}}{2} < 0 \tag{A.9}
\]
A particular solution of \(y\) from (A.8) is
\[
K_{21} = \frac{\bar{U}^2[y(1 + \beta c_2) - (p_1 - c) + 2c_1(\alpha - \bar{U}) - \gamma c_1(\alpha + 2\beta c_2 + \beta p_1)] + 2et\bar{U}(r + \delta)(1 + \beta c_2)}{2(1 + \beta c_2)[\bar{U}^2 + e\delta(r + \delta)] + \gamma^2\bar{U}^2c_1} \tag{A.10}
\]
Therefore, a general solution of \(y\) is
\[
y(t) = A_{21}e^{m_{21}t} + A_{22}e^{m_{22}t} + K_{21} \] which yields
\[
\lambda_1 = \frac{2e}{\bar{U}^2} \left(m_{21}A_{21}e^{m_{21}t} + m_{22}A_{22}e^{m_{22}t} + \delta A_{21}e^{m_{21}t} + \delta A_{22}e^{m_{22}t} + \delta K_{21} - \bar{U}l\right) \tag{A.11}
\]
Also, to guarantee that the limiting transversality condition \(lim_{T \to \infty} e^{-rT} \lambda_1(t) = 0\) holds for all parameters, \(A_{21} = 0\) \((: m_{21} - r > 0)\).

Therefore,
\[
y(t) = A_{22}e^{m_{22}t} + K_{21} \tag{A.12}
\]
\[
\lambda_1(t) = \frac{2e}{\bar{U}^2} [(m_{22} + \delta)A_{22}e^{m_{22}t} + \delta K_{21} - \bar{U}l] \tag{A.13}
\]
\[
v(t) = -\frac{\lambda_1\bar{U}}{2e} = -\frac{1}{\bar{U}} [(m_{22} + \delta)A_{22}e^{m_{22}t} + \delta K_{21} - \bar{U}l] \tag{A.14}
\]
\[
p_2(t) = \frac{1}{m_{22}} = \frac{\beta(1 + \beta c_2)}{2(1 + \beta c_2)} \frac{(\alpha + 2\beta c_2 + \beta p_1)}{2(1 + \beta c_2)} = \frac{\alpha(1 + 2\beta c_2) + \beta p_1}{2(1 + \beta c_2)} - \frac{\gamma(1 + 2\beta c_2)}{2(1 + \beta c_2)} y \tag{A.15}
\]
Calculate the coefficient using the initial condition gives \(A_{22} = y_0 - K_{21}\) and the long-term equilibriums are
\[
y^{ll}_{LR} \to K_{21} \tag{A.16}
\]
\[
v^{ll}_{LR} \to -\frac{1}{\bar{U}} (\delta K_{21} - \bar{U}l) \tag{A.17}
\]
\[
p^{ll}_{22LR} \to \frac{\alpha(1 + 2\beta c_2) + \beta p_1}{2(1 + \beta c_2)} - \frac{\gamma(1 + 2\beta c_2)}{2(1 + \beta c_2)} K_{21} \tag{A.18}
\]

**APPENDIX B**

**Proofs of Theorems**

**Proof of Theorem 1**
It is obvious from the analysis above that $K_{11} = K_{41}$ and $m_{12} = m_{42}$ holds, which leads to $A_{12} = A_{42}$. Therefore, $v^l = v^{IV}$ and $y^I = y^{IV}$ holds.

**Proof of Theorem 2**

Since $y^I = y^{IV}$ is proved in Theorem 1, we examine $y^{II}_L - y^{II}_R$ only.
\[
y^{II}_L - y^{II}_R = -\frac{1}{2f} K_{41} (r + \delta) - K_{21} \quad (B.1)
\]

Plugging the values of $K_{41}$ and $K_{21}$ into (B.1) and rearranging the equation, $y^{II}_L - y^{II}_R > 0$ is equivalent to
\[
(1 + \beta c_1 + \beta c_2)[f \bar{U}^2 + e\delta(r + \delta)] p_1 > [f \bar{U}^2 + e\delta(r + \delta)][(1 + \beta c_2)[c + 2c_1(\alpha - \bar{U})] - \alpha c_1(1 + 2\beta c_2)] - e\delta U c_1 \quad (B.2)
\]

Since $(1 + \beta c_1 + \beta c_2)[f \bar{U}^2 + e\delta(r + \delta)]$ is positive, (B.2) is equivalent to
\[
p_1 > \frac{[f \bar{U}^2 + e\delta(r + \delta)][(1 + \beta c_2)[c + 2c_1(\alpha - \bar{U})] - \alpha c_1(1 + 2\beta c_2)] - e\delta U c_1(r + \delta)}{(1 + \beta c_1 + \beta c_2)[f \bar{U}^2 + e\delta(r + \delta)]} = \bar{p}_1 \quad (B.3)
\]

Therefore, it holds that $y^{II}_L < y^I_L = y^{II}_R$, when $p_1 > \bar{p}_1$. Similarly, $v^{II}_L > v^I_L = v^{II}_R$ holds when $p_1 > \bar{p}_1$.

**Proof of Theorem 3**

Let $Q_1 = [f \bar{U}^2 + e\delta (r + \delta)]$ and $Q_2 = 4\beta(1 + \beta c_1 + \beta c_2)[f \bar{U}^2 + e\delta(r + \delta)] - \gamma^2 \bar{U}^2$. Note that $Q_2$ is positive since $K_{31}$ is assumed to be positive.

Since $y^I = y^{IV}$ is proved in Theorem 1, we examine $y^{IV}_L - y^{III}_R$ only.
\[
y^{IV}_L - y^{III}_R = -\frac{1}{2f} K_{41} (r + \delta) - K_{32} \quad (B.4)
\]

Plugging the values of $K_{41}$ and $K_{32}$ into (B.4) and utilizing $Q_1$ and $Q_2$, $y^{IV}_L - y^{III}_L > 0$ is equivalent to
\[
y^{IV}_L - y^{III}_L = \alpha > e\delta U(\gamma^2 \bar{U}^2 - \beta \gamma \bar{U}^2) \quad (B.5)
\]

Since $y^{IV}_L > y^{III}_L$ is positive, (B.5) is equivalent to
\[
\alpha > \frac{e\delta((r + \delta)\gamma \bar{U}) - \beta(2c_1 \bar{U} - c)}{\gamma^2 \bar{U}^2} = \bar{\alpha} \quad (B.6)
\]

Therefore, it holds that $y^{III}_L < y^I_L = y^{IV}_R$, when $\alpha > \bar{\alpha}$. Similarly, $v^{III}_L > v^I_L = v^{IV}_R$ holds, when $\alpha > \bar{\alpha}$.

Furthermore, since $D = \alpha - \beta p_2 - \gamma y$ in model 3, the long-term demand is
\[
D^{III}_L = \alpha - \beta p^{III}_L - \gamma y^{III}_L = \alpha - \beta \left[\frac{\alpha(1 + 2\beta c_1 + 2\beta c_2) - 2\beta c_1 \bar{U} - 2\beta \gamma \bar{U}}{2(1 + \beta c_1 + \beta c_2)} - \frac{\gamma(1 + 2\beta c_1 + 2\beta c_2)}{2(1 + \beta c_1 + \beta c_2)} K_{32}\right] - \gamma K_{32}
\]

\[
= \frac{1}{2(1 + \beta c_1 + \beta c_2)} \alpha + \frac{2\beta c_1 \bar{U} - \beta c}{2(1 + \beta c_1 + \beta c_2)} - \frac{\gamma}{2(1 + \beta c_1 + \beta c_2)} \frac{4\beta \gamma \bar{U}(1 + \beta c_1 + \beta c_2)(r + \delta) - \gamma \bar{U}^2(\alpha - \beta c + 2\beta c_1 \bar{U})}{4\beta (1 + \beta c_1 + \beta c_2)[f \bar{U}^2 + e\delta(r + \delta)] - \gamma^2 \bar{U}^2} \quad (B.7)
\]

For the long-term demand to be positive, rearranging the equation (B.7),
\[
\alpha + 2\beta c_1 \bar{U} - \beta c - \frac{4\beta \gamma \bar{U}(1 + \beta c_1 + \beta c_2)(r + \delta) - \gamma \bar{U}^2(\alpha - \beta c + 2\beta c_1 \bar{U})}{4\beta (1 + \beta c_1 + \beta c_2)[f \bar{U}^2 + e\delta(r + \delta)] - \gamma^2 \bar{U}^2} > 0 \quad (B.8)
\]
Therefore, \( D_{LR}^{II} > 0 \) holds if and only if \( \alpha > \frac{e^0(r+\delta)u^0}{(f + e\delta(r+\delta))} - \beta(2c_1u - c) = \tilde{\alpha} \)

**Proof of Theorem 4**

**Part 1**

\[
\frac{\partial y_{LR}^I}{\partial f} = -\frac{\tilde{u}^2}{(f + e\delta(r+\delta))^2} \cdot eU(l(r + \delta) < 0 (B.9)

It is obvious that (B.9) holds because all parameters are positive.

Similarly, \( \frac{\partial y_{LR}^I}{\partial f} = -\frac{\tilde{u}^4}{(f + e\delta(r+\delta))^2} + \frac{\tilde{u}^2}{(f + e\delta(r+\delta))^2} = \frac{e\tilde{u}^2\delta(r+\delta)}{(f + e\delta(r+\delta))^2} > 0 \).

Since \( y_{LR}^I = y_{LR}^IV \) and \( v_{LR}^I = v_{LR}^IV \), it also holds that \( \frac{\partial y_{LR}^IV}{\partial f} < 0, \frac{\partial y_{LR}^IV}{\partial f} > 0 \).

**Part 2**

\[
\frac{\partial y_{LR}^II}{\partial f} = -\frac{2\tilde{u}^2(1 + \beta c_2)}{(2 + \beta^2 c_2)[f + e\delta(r+\delta)]} \cdot \{\tilde{u}^2(\gamma(1 + \beta c_2)(-\mu - c) + 2c_1(\alpha - \tilde{u}) - \gamma c_1(\alpha + 2\alpha c_2 + \beta \kappa)) + 2\epsilon l\tilde{u}(r + \delta)(1 + \beta c_2)\}
\]

Utilizing the value of \( K_{21} \), \( \frac{\partial y_{LR}^II}{\partial f} < 0 \) is equivalent to

\[
-\frac{2\tilde{u}^2(1 + \beta c_2)}{(2 + \beta^2 c_2)[f + e\delta(r+\delta)]} \cdot K_{21} < 0 (B.11)
\]

Note that \( K_{21} \) is assumed to be nonnegative for feasible controls. Therefore, (B.11) holds.

Similarly, \( \frac{\partial y_{LR}^IV}{\partial f} = \frac{2\tilde{u}^2(1 + \beta c_2)}{(2 + \beta^2 c_2)[f + e\delta(r+\delta)]} \cdot K_{21} > 0 \)

**Part 3**

\[
\frac{\partial y_{LR}^II}{\partial f} = -\frac{4\tilde{u}(1 + \beta c_2)(1 + \beta c_2)\tilde{u}^2}{(4\beta(1 + \beta c_1 + \beta c_2)[f + e\delta(r+\delta)] - \gamma^2 \tilde{u}^2)^2} \cdot [4\beta e\tilde{u}(1 + \beta c_1 + \beta c_2)(r + \delta) - \gamma \tilde{u}^2(\alpha - \beta c + 2\beta c_1 \tilde{u})]
\]

Utilizing the value of \( K_{32} \), \( \frac{\partial y_{LR}^II}{\partial f} < 0 \) is equivalent to

\[
-\frac{4\tilde{u}(1 + \beta c_1 + \beta c_2)\tilde{u}^2}{(4\beta(1 + \beta c_1 + \beta c_2)[f + e\delta(r+\delta)] - \gamma^2 \tilde{u}^2)^2} \cdot K_{32} < 0 (B.13)
\]

Note that \( [4\beta(1 + \beta c_1 + \beta c_2)[f + e\delta(r+\delta)] - \gamma^2 \tilde{u}^2] > 0 \) since \( K_{31} \) is assumed to be positive. Also, \( K_{32} \) is assumed to be nonnegative for feasible controls. Therefore, (B.13) holds.

Similarly, \( \frac{\partial y_{LR}^IV}{\partial f} = \frac{4\tilde{u}(1 + \beta c_1 + \beta c_2)\tilde{u}^2}{(4\beta(1 + \beta c_1 + \beta c_2)[f + e\delta(r+\delta)] - \gamma^2 \tilde{u}^2)^2} \cdot K_{32} > 0 \).

**REFERENCES**


