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以綠色導向政策探討低經濟價值再生材料之回收供應鏈

Green Policy-Driven Closed-Loop Supply Chain for Recycling of Economically-Disadvantaged Recycled Materials

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摘 要

本文探討對於低經濟價值再生材料 (EDRMS) 在低利潤資源回收上，如何制定相關有效的環境政策。經過深入分析，我們提出一個政策工具，其立論是基於順序競爭賽局的多層次閉環供應鏈模型，體現互相競爭的製造商、原生和再生材料供應商以及政府之間的相互作用。分析結果表明，目前的稅收補貼制度是有效的，因為這一政策提高了參與回收系統各方公司的利潤。我們建議政府應該多關注低利潤資源回收的政策制度。

【關鍵字】綠色供應鏈管理、賽局理論、稅收補貼制度、低利潤資源回收、低經濟價值再生材料 (EDRM)

Abstract

This paper investigates an effectiveness problem in the enactment of environmental policies aimed at profitless recycling of economically-disadvantaged recycled materials (EDRMs). After thorough analysis, a policy instrument has been proposed. The arguments are established from a closed-loop supply chain model in a multiplayer hierarchical Stackelberg game, manifesting interactions between competing manufacturers, suppliers of virgin and recycled materials, and the government. Analytical results indicate that a tax-subsidy system is effective because this policy improves the profits of all parties involved in the recycling system. We suggest that governments should involve in the recycling practice of profitless materials.

【Keywords】green supply chain management, game theory, tax-subsidy system, profitless recycling, economically-disadvantaged recycled materials (EDRM)

1. Introduction

Economically-disadvantaged recycled materials (EDRMs) refer to materials without recycling value (Hawken, Lovins, and Lovins, 2000). Green supply chain management (GSCM) and recycling practice have gained prominence due to global environmental concerns. However, the current booming recycling business is completely driven by profitability. Some materials have been recycled perfectly without any help from public authorities, while the rest of the materials that lack economic value and bring damage to the environment are only partially handled due to the limited financial rewards from the government. Thus, the unprocessed parts become a cumulative burden for the general public.

For example, most precious metals are valuable and their recycling systems are efficient and effective. The technologies and markets in metal materials recovery are usually advanced. On the other hand, a mass of materials has long been left behind from the value chains of the business world (International EPS Alliance [INEPSA], 2013). For example, most composite materials are almost impossible or extremely costly to be processed (Smith and Shiau, 1998; EarthTalk, 2013). Recycling glass products yields low financial return. Plastic materials are complex in composition and mixing some of them may cause severe consequences (Earth911, 2013). Scraps containing such materials have to be piled up or dumped unless significant technological advances emerge (Gesing, 2013), or sufficient financial aid from the government is expected (Nidumolu, Prahalad, and Rangaswami, 2009).

Some governments around the globe enact laws requiring minimum use of recycled materials, such as the EcoMark in Japan (Japan Environment Association, 2007). Some manufacturers such as Toyota (Pristin, 2003; Toyota, 2014) and Sharp (Sharp Corp, 2014) promote the usage of recycled materials. Automobile manufacturers encounter fierce competition on one hand (Toyota, 2014), and keep applying more recycled materials on the other hand to create competitive advantage (Clean Auto, 2009).

This paper investigates the conditions that motivate manufacturers to reuse EDRM under which the acquisition cost is high and the final product quality is low. With deliberation, an intuition expects that individual governments can force producers to use more EDRMs. However, unconditional coercion may force them out of the market. Another intuition can create a reasonable tax-subsidy system, using economical means to absorb regulation impact. Nevertheless, not all governments hold such superior power. This study therefore tries to find further conditions that motivate producers to use EDRM while maintaining their market competitiveness. EDRMs possess several disadvantages, preventing its usage by an ordinary manufacturer, e.g., most composite material products and construction wastes (The Economist, 2002). For example, cost savings from procuring EDRMs may not be proportionate to quality loss or degeneration in the final product. While supply source is constantly unsteady and unsecure, EDRMs also suffer from indefinite delivered quantity and possibly high acquisition costs. Furthermore, unlike virgin materials, EDRMs usually have limited applications, are consumed in small amounts, and account for only a fraction of the entire bill of materials; hence they are often not prioritized in material usage. Owing to the challenges, previous literature leaves space for our improvement in addressing the issues of a closed-loop supply chain for EDRMs. The following research questions are addressed: How can a EDRM supply chain be sustainable without artificially enforcing the minimum content of EDRM in the final products? When will a EDRM closed-loop supply chain sustain without government intervention?

Our outcomes suggest that a simple subsidy mechanism in cost-based taxing (Dobbs, 1991) can encourage a manufacture to employ more EDRMs. We suggest that governments should get involved in recycling such profitless materials. The manufacturers can therefore rely on the decisions of both governments and EDRM suppliers in determining the production amount of green products.

2. Related Literature

Although managerial topics in material recovery have been studied extensively, most studies ignore the heterogeneity in material characteristics and underestimate the difficulty in recycling certain kinds of materials. For instance, closed-loop systems are limited to investigating the interaction between members such as manufacturers and retailers, in dealing with end-of-life product collection, but supply chain behavior caused by material heterogeneity and economic market viability is disregarded (The Economist, 2002).

Because of the low economic value and inferior channel power, EDRMs behave differently in conventional economic instruments. Poor handling of EDRMs discourages the industry from collecting these materials. Consequently, based on the GSCM concepts proposed by Majumder and Groenevelt (2001), Ferrer and Swaminathan (2006), and Sheu and Talley (2011), this paper investigates how economic instruments and product quality loss dictate the aggregate decisions of key members in a green supply chain in the strategic planning domain.

The gaps in existing research present a research opportunity for the current study, which concerns the use of recycled materials in the industrial market rather than in the consumer market. We focus on the challenge of encouraging the transportation of EDRMs for voluntary consumption by considering effective economic instruments and different configurations of the green supply chain system driven by economic incentives. Although remarkable progress has been made by pioneering studies in promoting material recycling, several critical issues remain unsolved and thus motivate this study. Sheu, Chou, and Hu, (2005), Sheu and Chen (2014), and Chen and Sheu (2009) suggested the use of economic instruments in strategic planning for a closed-loop supply chain. Drawing on global green legislation, such as the Waste Electrical and Electronic Equipment Directive, Fleischmann, Kuik, and Dekker (2002) argued that government standards are at least indispensable in correcting the market failure of EDRMs, promoting awareness of pollution reduction, and imposing responsibility on manufacturers.

Literature on recycling and closed-loop supply chains has only partially discussed the effects of competition (Majumder and Groenevelt, 2001; Debo, Toktay, and Van Wassenhove, 2005; Ferrer and Swaminathan, 2006). The use of economic incentives to promote material recycling has also been extensively investigated in environmental economics (fnUlph, 1996; Walls and Palmer, 2001; Benchekroun and Van Long, 2002). Ferrer and Swaminathan (2006) facilitated competition in manufacturing operations in monopoly and duopoly environments under the assumption of the homogeneous value of recycled materials. Competition should be addressed in environmental policy because its effectiveness heavily depends on market response. Without competition, manufacturers can easily transfer their environmental cost to consumers by raising selling prices. Even in a mandatory recycling system, manufacturers can still transfer responsibility to third parties without altering their production formula.

Given that previous studies rarely considered the value and cost of designing incentive mechanisms and thus resulted in unbalanced literature on closed-loop supply chains, we focus on the economic issue in the manufacturing market rather than the consumer market and consequently build a quantity competition model for the industrial market. A manufacturer’s decisions, such as that for production quantity, determine the operational strategies of an integrated supplier moving toward equilibrium conditions driven by governmental economic incentives. The manufacturer must rely heavily on the decisions of both governments and EDRM suppliers in determining the production amount of green products in green supply chains.

3. A Closed-Loop Supply Chain Model

The problem in this study involves a virgin material supplier and an EDRM supplier, which collects end-of-life product and provides recovered materials under the subsidy of the government, as shown in Figure 1. A group of manufacturers take materials from both suppliers, pay environmental tax to the government, and sell the final products to the market. The problem is postulated as maximizing the profits of all parties, including the profits of the manufacturers and suppliers, and the social welfare in the entire closed-loop supply chain and the environment.

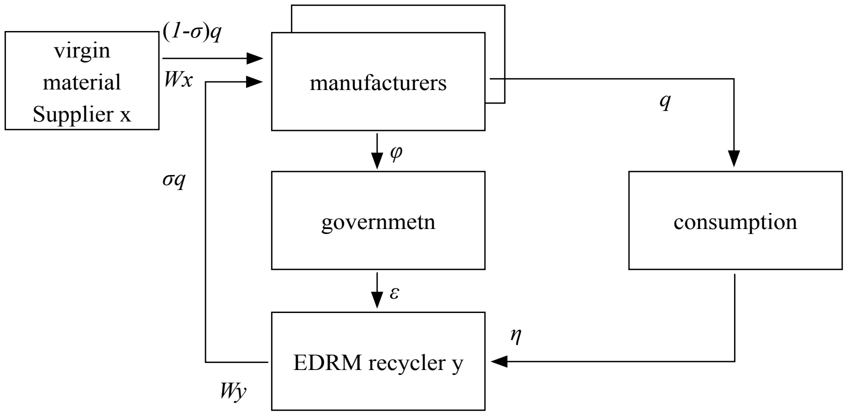

Figure 1 Players and Key-Variables in a Supply Chain Network

We assume the market perform adopt Cournot competition and the inverse demand function satisfies $p = 1\text{-}\sum q_i$. Manufacturers produce total demand $q = \sum_{i=1}^{n} q_i$, where q_i represents the demand of manufacturer i and n denotes the number of the competitive manufacturers involved in the system.

Each manufacturer design its products with a predetermined ingredient and a design specification fulfilling eco-design principles. The ingredient comprises 1-σ virgin materials and σ EDRMs and the eco-design associates to the level of effluent ξ. The ingredient and effluent can either be determined by law or by accommodating to an existing verified processing ingredient. For example, (Molding) (Lead-free Solider) We set the variables σ and ξ as exogenous to the optimization framework so that further strategic analysis can be applied to the variables. These two exogenous decisions are crucial for promoting voluntary improvement of product greenness. They are often strategic for the business and may not apply to the maximum rationality in optimization. For example, the decision of EDRM mixture σ is often driven by the procurement cost while the environmentally friendly product design ξ is determined by the level of acceptance in the consumer market. On the other hand, the ingredient mixture and product composition are costly in realizing frequent change. They can take as given for the purpose of analysis in this paper.

To urge manufacturers to move toward GSCM, government agencies plan to apply economic instruments – a pollution tax (denoted by ϕ for producing one unit of a manufactured product) and a subsidy (denoted by ε for recycling one unit of an end-of-life product) – to manufacturers in charge of manufacturing and end-of-life product recycling. This study employs a variable rate tax, which depends on product eco-design or the level of effluent ξ. Governments collect less tax if the product emits less effluent. In this study, the amount of tax is linear to the effluent, that is, $\phi_i \xi_i$.

The game in the analysis is Stackelberg. The government acts as the first leader and the two suppliers are the second leaders, and the manufacturers follow the actions. By above set of game, the relationship among each player can then be readily induced. We begin modeling the closed-loop supply chain by manufacturers' profits: $\pi_{mi} = pq_i - (\tilde{w}_{x_i}\sigma_{xi} + \tilde{w}_{y_i}\sigma_{yi})q_i - \tilde{c}_{m_i}q_i - \phi_i\xi_i q_i$, where w_x and w_y are the wholesale prices for manufacturer i for procuring a unit of virgin and recycled materials, respectively, and $\tilde{c}_{m_i}$ is the marginal cost of producing a unit of products. The virgin-material supplier can determine its wholesale price w_{xi} to each manufacturer and seek to maximize profit $\pi_x = \sum_{i=1}^{n} \tilde{w}_{x_i}\sigma_{xi}q_i - c_x\sigma_{xi}q_i$, where c_x denotes the marginal cost for generating a unit of virgin materials. The EDRM material supplier also determines its wholesale price $\tilde{w}_{y_i}$ to each manufacturer and seeks to maximize profit $\pi_y = \sum_{i=1}^{n}(\sigma_{y_i}\tilde{w}_{y_i} - \tilde{c}_y\sigma_{y_i})q_i - c_h h_i - c_u(1\text{-}\eta)h_i + \tilde{\varepsilon}h_i$, where c_h and c_u are the marginal costs of collecting and final disposal of the waste.

We temporarily use a $\tilde{w}$ notation here and this one will be substituted by a new symbol w later for a simplification of notations. In response to the legislative requirements for the input amount of EDRMs to produce a unit of product as well as the recycled-material supply process, the system converts waste into usable materials, at which $\sigma y_i q_i = \eta h_i$ at a fixed conversion rate η. Assuming a long-term flow balance condition in the closed-loop supply chain, the h_i part in the profit of EDRM supplier can be replaced by $\sigma y_i q_i/\eta$.

The government's optimal decisions with respect to the environmental taxes (ϕ) and subsidies ($\tilde{\varepsilon}$) for managing recycled-material supply chain members are developed as the Stackelberg first leader. Drawing from the concept of social welfare (SW) maximization widely used in previous literature focused on green policy determination (Dobbs, 1991; Walls and Palmer, 2001), we argue that the main items considered in the government's objective function are as follows: (1) consumer surplus (CS); (2) producer surplus (PS); and (3) environmental cost (EC). Therefore, the government's objective function is $SW = \pi_{CS} + \pi_{PS} + \pi_{EC}$, where $\pi_{CS} = (\sum q_i)^2$, $\pi_{PS} = \pi_m + \pi_x + \pi_y$, $\pi_{EC} = \kappa \sum \sigma_{yi} q_i$, and κ represents the environmental benignity factor for applying EDRM.

We can further simplify the representation further by representing in matrix form and substituting in variables with terse forms. Let $w_{xi} = \sigma_{xi} \widetilde{w}_{x_i}$, $w_{yi} = \sigma_{yi} \widetilde{w}_{y_i}$, $c_y = \tilde{c}_y + \frac{c_h + c_u(1-\eta)}{\eta}$, $\varepsilon = \frac{\tilde{\varepsilon}}{\eta}$, $\hat{c}_{m_i} = \tilde{c}_{m_i} - 1$, $c_{mi} = -\hat{c}_{m_i}$, $\sigma_{yi} = \sigma_i$, and $\sigma_{xi} = 1 - \sigma_i$. Note that $c_{mi} < 0$. Vectors are written in fold face fonts, i.e., $w_x = (w_{xi})_{i=1\ldots n}$, $\sigma = (\sigma_i)_{i=1\ldots n}$ and $c_m = (c_{mi})_{i=1\ldots n}$. Substitute the notations into the original problem and we have the following abstract expression:

$$\pi_m = (1 - 11'q) \circ q - (w_x + w_y) \circ q - (1 - c_m + \phi\xi)q,$$
$$\pi_x = (w_x - c_x 1 + c_x \sigma)'q,$$
$$\pi_y = (w_y - c_y \sigma + \varepsilon\sigma)'q,$$
$$\mathrm{SW} = ((c_x - c_y + \varepsilon + \kappa)\sigma - (c_x 1 - c_m + \phi\xi))'q$$

Recall that the differentiation in the Hadamard product has the following relations, $\frac{\partial}{\partial \boldsymbol{q}} \circ q$ and $\frac{\partial}{\partial \boldsymbol{q}} \circ (11'q \circ q) = q + 11'q$, where 1 and I are unit vector and identity matrix, respectively, and $(\cdot)'$ denotes a vector transpose. The operator $\succ$ represents a component-wise comparison. For simplification of notation, we introduce a demand conversion matrix $\mathcal{J} = (\mathrm{I}+11')^{-1}$, with properties $1'\mathcal{J} = (\mathrm{n}+1)^{-1}1^{-1}$, $11'\mathcal{J} = \mathrm{I} - \mathcal{J}$, and $1'\mathcal{J}1 = n(\mathrm{n}+1)^{-1}$. In the next section, we will show this matrix serves a similar purpose of a demand function that converts price to production quantity.

4. Policy Frameworks

This section demonstrates the effectiveness of a tax-subsidy mechanism for recycling EDRMs. We rationalize the decision-making process among governments and green supply chain members. In the hierarchical game context, all parties observe the intensity of incentives implemented by governments (e.g., environmental management fees and taxes). Further decisions are made by all material suppliers in competitive green supply chains in response to the government agency. The product market finally speculates about the potential decisions of green supply chain members in the process of determining the optimal competitive production quantities. We maximize the social welfare in the entire closed-loop supply chain and the environment as well as profits of all agents in a sense of Nash equilibrium. We will characterize the decision impact to material suppliers and social welfare in this section.

We analyze the effectiveness of policy frameworks in which governments do not clearly define the bottom line for the minimum amount of EDRMs to be used. To prove the effectiveness, the results of the tax-subsidy mechanism are compared to the situation with no government intervention.

The following policy frameworks are considered: (1) (0S) no recycling is performed; (2) (2S⁻) a recycling system without subsidy implemented; (3) (2S) a subsidy is given to the EDRM supplier and product value remains unchanged. The first two frameworks are merely for benchmarking purpose, and they are able to show the effectiveness of the taxes and subsidies.

We first investigate a base model with only a virgin material supplier. In this base model, a supply chain does not recycle and involves manufacturing activity only.

Lemma 1. ((0S) *virgin material only*). The optimal sales quantities for manufacturers are

$$q^{*(0S)} = \frac{1}{2}\mathcal{J}(\mathrm{c}_m - c_x 1) \tag{1}$$

The optimal wholesale prices of virgin material for manufacturers are

$$w_x^{*(0S)} = \frac{1}{2}(c_x 1 + \mathrm{c}_m) \tag{2}$$

The optimal wholesale prices of virgin material for manufacturers are

$$\pi_m^{*(0S)} = q^{*(0S)} \circ q^{*(0S)} \tag{3}$$

From Lemma 1, it follows that higher manufacturing cost and material cost make the supplier raise the wholesale price and the manufacturers will produce more quantity to compensate the cost increase. Because of our simplification and derivation, all manufacturer profits in the consequent analysis become a quadratic form of production quantities. For comparison purpose, the next analysis discusses the supply chain behavior under which the EDRM supplier competes with a virgin material but no tax-subsidy mechanisms in place (2S⁻).

Lemma 2. ((2S⁻) *two suppliers without subsidy*). The optimal sales quantities for manufacturers are

$$q^{*(2S^-)} = \frac{1}{3}\mathcal{J}\left((\mathrm{c}_m - c_x 1) - (c_y - c_x)\sigma\right) \tag{4}$$

The optimal wholesale prices are

$$w_x^{*(2S^-)} + w_x^{*(2S^-)} = \frac{1}{3}\Big((c_x 1 + 2\mathrm{c}_m) + \big(c_y - c_y\big)\sigma\Big) \tag{5}$$

The optimal profit for each manufacturer is

$$\pi_m^{*(2S^-)} = q^{*(2S^-)} \circ q^{*(2S^-)} \tag{6}$$

From Lemma 2, in addition to above-mentioned manufacturing cost factors, it follows that the material cost differential ($c_y - c_x$) will further decrease the equilibrium manufacturing quantity for the case of two suppliers without subsidy. It shows the use of EDRMs will reduce the profit of manufacturer. If no proper intervention is introduced, it is definite that no manufacturer will voluntarily use such materials. Now we consider the policy framework (2S) in which a virgin material supplier *x* and an EDRM supplier *y* coexist, and the subsidy goes to the EDRM supplier. Define an ingredient variability matrix as

$$\mathrm{R} = \begin{bmatrix} \mathcal{I}_{\sigma\sigma} & \mathcal{I}_{\xi\sigma} \\ \mathcal{I}_{\xi\sigma} & \mathcal{I}_{\xi\xi} \end{bmatrix}, \tag{7}$$

where the ingredient cross variabilities are $\mathcal{I}_{\xi\xi} \triangleq \xi'\mathcal{I}\xi$, $\mathcal{I}_{\sigma\sigma} \triangleq \sigma'\mathcal{I}\sigma$, $\mathcal{I}_{\xi\sigma} \triangleq \xi'\mathcal{I}\sigma$, $\mathcal{I}_{\xi m} \triangleq \xi'\mathcal{I}(\mathrm{c}_m - c_x 1)$, and $\mathcal{I}_{\sigma m} \triangleq \sigma'\mathcal{I}(\mathrm{c}_m - c_x 1)$. Because the matrix $\mathcal{I}$ is positive definite, all cross variabilities are positive. The ingredient variability matrix is assumed to be diagonally dominant. $\mathcal{I}_{\xi\xi}\mathcal{I}_{\sigma\sigma} > \mathcal{I}_{\xi\sigma}^2$, that is, the variability within the same variables is greater than variability between σ and ξ.

Proposition 1. ((2S) *Nash equilibrium*). Given EDRM percentage σ and the product designs ξ, we have the following Nash equilibriums and they are unique.

(i) The optimal governmental decisions

$$\begin{bmatrix} \phi^{*(2S)} \\ \varepsilon^{*(2S)} \end{bmatrix} = \begin{bmatrix} 0 \\ c_y - c_x - \frac{1}{2}\kappa \end{bmatrix} + \mathrm{R}^{-1}\begin{bmatrix} \mathcal{I}_{\sigma m} \\ \mathcal{I}_{\xi m} \end{bmatrix} \tag{8}$$

(ii) The optimal sales quantities for manufacturers

$$q^{*(2S)} = \frac{1}{3}\mathcal{I}\Big(\varepsilon\sigma - \phi\xi - \big(c_y - c_x\big)\sigma + (\mathrm{c}_m - c_x 1)\Big). \tag{9}$$

(iii) The optimal wholesale prices for suppliers are

$$w_x^{*(2S)} + w_y^{*(2S)} = \frac{1}{3}\Big(\big(c_y - c_x - \varepsilon\big)\sigma + 2c_m + c_x 1 - 2\phi\xi\Big). \tag{10}$$

From Proposition 1, we know that the tax rate is always positive and the subsidy rate is positive because $c_y > c_x$. Given that all the decisions are in equilibrium, increase of EDRM mixture or reduction of the product effluents will effectively increase the total quantity consumption (9) and encourage the recycling of EDRMs. Although the manufacturers have been charged tax, they earn more profit than the system without tax-subsidy. The long-term financial balance of the tax and subsidy will be maintained in the future adjustment of product design and material mixture. Currently, many governments collect money from producers in a form of Advance Disposal Fee (Walls and Palmer, 2001). The money they collected must be saved for a fund because a large portion of the fund will go to process colossal amount of historical waste. Beside the maintenance of the fund, more importantly, we demonstrate in the next analysis that government intervention can effectively encourage manufacturers to use more EDRMs.

Proposition 2. ((2S) *Performances*). Let $y = (\varepsilon\sigma - \phi\xi - (c_y - c_x)\sigma + (c_m - c_x 1))$. The social welfare is

$$SW^{*(2S)} = \frac{1}{3}(y + \kappa\sigma)'\mathcal{J}\, y \tag{11}$$

the two suppliers jointly make profit is

$$\pi_x^{*(2S)} + \pi_y^{*(2S)} = \frac{2}{9} y'\, \mathcal{J}\, y \tag{12}$$

and the optimal profits for all manufacturers are

$$\pi_m^{*(2S)} = q^{*(2S)} \circ q^{*(2S)} \tag{13}$$

Given the synthetic quantity, y, profits of all parties and social welfare are easily presented in Proposition 2. With the clear understanding in the consequence of tax-subsidy, we are able to compare the improvement of tax-subsidy.

Proposition 3. (*tax-subsidy improvement*). The tax-subsidy policy framework does improve the total social welfare as well as the profits of both material suppliers and manufacturers, that is,

$$SW^{*(2S)} > SW^{*(2S^-)} \tag{14}$$

$$\left(\pi_x^{*(2S)} + \pi_y^{*(2S)}\right) > (\pi_x^{*(2S^-)} + \pi_y^{*(2S^-)}) \tag{15}$$

$$1'\pi_m^{*(2S)} > 1'\pi_m^{*(2S^-)} \tag{16}$$

The results of Proposition 1 and 2 have specifically answered the research questions listed in Section 1. If the tax and subsidy instrument (8) are implemented, eco-friendly manufacturers will be more willing to increase its production quantity and more dedicated EDMS facilities will be established. With the proper internalization of externality, containing less EDRMs will be punished in the production cost and, therefore, the optimal production quantity will decrease. Proposition 3 confirms that the common tax-subsidy policy instrument can improve chain members' profits and therefore can help to promote the collecting and processing of EDRM.

Regarding to recycling a material or digesting a pile of waste, there is a conflict goal. A real-world example of a multiplayer problem in enacting environmental policy is demonstrated for the effectiveness of the proposed policy instrument. Recently, the plastic material Polylactide (PLA) is getting popular because of its biodegradable property (Vink, Rábago, Glassner, and Gruber, 2003). We know that, subject to the limited ability and financial driver of collecting logistics, not all end-of-life products can be perfectly handled. The industry wants to invent a material that can be reused for many times if it has been collected but it should be bio-degenerated if it has been disposed. Unfortunately, there is no single material having both advantages. Even more unfortunately, these two materials are not mixable in the recycling process. Polyethylene terephthalate (PET) recyclers do not welcome the use of PLA as general public does because a slight contamination of PLA into recycled PET will cause the entire materials unusable (Madival, Auras, Singh, and Narayan, 2009). Few facilities can receive profit from handling this kind of material. The ought-to-be environmentally friendly superstar becomes today's EDRM. Fortunately, a simple tax-subsidy can put momentum into the collection system. Many governments, such as Germany, France, Korea, Italy, and Taiwan, have established tax-subsidy regulation to encourage the collection and processing of biodegradable plastics (Jem, van der Pol, and de Vos, 2010).

5. Numerical Example

Consider the practice of PVC plastics recycling and material usage (Lenntech, 2014). The reuse technology of this material has been confirmed by industries both in the chemical process of refinery and the mechanism process of injection molding (Gordon, 2010). Molding in general is deemed highly experimental. Most recipes for injection molding are usually designed for a particular ingredient and percentage of plastics and additives. Mixing recycled and virgin PVC is possible but the shaping mold has to be specially designed and fine-tuned for a particular recipe. Because the expensive equipment, machines, and devices can only be setup for one set of parameters, the percentage usage of recycled PVC will not change easily.

We assume the suppliers in PVC closed-loop supply chain have $c_x = 0.2$ for the virgin VPC and $c_y = 0.4$ for the recycled PVC. The environmental benignity factor $\kappa = 0.2$. There are 3 manufacturers get σ_i proportion of recycled materials from the EDRM processor and get virgin materials for the rest of inputs. If the system use virgin materials only, the 3 manufacturers will all produce quantities $q^0 = [(0.05\ 0.05\ 0.05)]$ because all of them have the same $\tilde{c}_{m_i} = 0.4$.

Furthermore, for a market providing both virgin and recycled materials but no government intervention, the 3 manufacturers will produce quantities $q^{(2S-)} = [(0.0333\ 0.0267\ 0.0200)]$. The ingredients of the 3 manufacturers are shown in the second column of Table 1. Without the help of government, the cost of providing EDRMs is more expensive than that of virgin materials. Therefore, containing more EDRMs causes a decrease in production and Manufacturer 3 held the least market share.

Table 1 Parameters and Equilibrium Results for the 3 Manufacturers

Manu.	σ_i	ξ_i	$\tilde{c}_{mi}$	w_{xi}^*	w_{yi}^*	q_i^*	π^*_{mi}
1	0.3	0.6	0.4	0.2814	0.0533	0.0178	0.0003
2	0.4	0.5	0.4	0.2847	0.0473	0.0412	0.0017
3	0.5	0.4	0.4	0.2880	0.0413	0.0645	0.0042

To evaluate the amount of tax and subsidy, we calculate $\mathcal{J} = \frac{1}{4}\begin{bmatrix} 3 & -1 & -1 \\ -1 & 3 & -1 \\ -1 & -1 & 3 \end{bmatrix}$, $\mathcal{J}_{\xi\xi} = 0.2075$, $\mathcal{J}_{\sigma\sigma} = 0.1400$, $\mathcal{J}_{\xi\sigma} = 0.1300$, $\mathcal{J}_{\xi m} = 0.1500$, and $\mathcal{J}_{\sigma m} = 0.1200$. The amounts become $\phi = 0.2065$ and $\varepsilon = 0.6935$.

We compare the profits and social welfares between policy framework ($2S^-$) and (2S). With the government intervention, both social welfare and company profit become higher, that is, $SW^{*(2S-)} = 0.0320$ and $SW^{*(2S)} = 0.0751$ while $\sum\pi_{m_i}^{*(2S^-)} = 0.0022$ and $\sum\pi_{m_i}^{*(2S)} = 0.0062$. Manufacturer 3 used the most EDRM and emitted least effluent so that Manufacturer 3 has been encouraged to produce the most in the market.

6. Conclusions

This paper investigates the potential effects of governmental economic incentives and policy frameworks on operational decisions and performance for the goal of promoting GSCM. Our work contributes to the literature in several folds. The first is the involvement of governments and their economic incentives into a closed-loop supply chain model for adding insight into the effects of governmental economic incentives on performance toward GSCM. Second, this work conceptualized a profitless recycling practice among closed-loop supply chain members in response to governmental economic instruments promoting movement toward equilibrium conditions. Governments can play the role of a mediator to facilitate the interaction between supply and reverse-supply chains, thereby promoting usage of EDRMs.

In this study, we argue that the recycled-material supplier should bear subsidies from governments to encourage the recycling of EDRMs. Manufacturers will therefore decide to produce more products with containment of recycled materials. At the same time, based on the concept of extended producer responsibility, the manufacturers should be taxed for producing eco-friendly products. Therefore, the manufacturer’s decisions, such as that related to production quantities, principally rely on the recycled-material supplier’s operational strategies toward equilibrium conditions driven by governmental economic incentives.

Appendix for Theorem Proofs

Proof of Lemma 1.

The virgin material based model problem and the profits can be rewritten as

$$\pi_m(q) = (1 - 11'q) \circ \mathrm{q} - (\mathrm{w_x} + 1 - c_m) \circ q$$

$$\pi_x = (w_x - c_x 1)' q,$$

To find the optimal q vector, take derivative of π_m with respect to q. Let $\mathcal{J}: = (\mathrm{I}+11')^{-1}$. Drawing from the first-order condition, we can readily derive the corresponding equilibrium solution

$$\frac{\partial}{\partial q} \circ \pi_m = 1 - (\mathrm{I} + 11')\mathrm{q} - (w_x + 1 - c_m) = 0,$$

$$q^* = -\mathcal{J}(w_x - c_m)$$

For the intermediary leader, substitute q^* into π_x, and evaluate the Nash equilibrium as follows:

$$\frac{\partial \pi_x}{\partial w_x} = -\mathcal{J}(2w_x - c_x 1 - c_m) = 0.$$

Therefore the equilibrium solutions w_x and $q^{*(0S)}$ are then obtained as

$$2w_x = c_x 1 + c_m \text{ and } q^* = \frac{1}{2}\mathcal{J}(c_m - c_x 1).$$

Proof of Lemma 2.

$$\frac{\partial}{\partial q} \circ \pi_m = 1 - (\mathrm{I} + 11')\mathrm{q} - \left(w_x + w_y + 1 - c_m\right) = 0,$$

$$q^* = -\mathcal{J}(\mathrm{w_x} + w_y - \mathrm{c_m})$$

For the intermediary leader, substitute q^* into π_x and π_y, and evaluate the Nash equilibrium as follows:

$$\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} w_x \\ w_y \end{bmatrix} = \begin{bmatrix} c_x 1 - c_x\sigma + c_m \\ c_y\sigma + c_m \end{bmatrix}.$$

Therefore the equilibrium solutions w_x, w_x, and $q^{*(2S-)}$ are obtained as

$$3\left(w_x + w_y\right) = (c_x 1 + 2c_m) + (c_y - c_x)\sigma, \text{ and } q^* = \frac{1}{3}\mathcal{J}\left((\mathrm{c}_m - c_x 1) - (c_y - c_x)\sigma\right).$$

Proof of Proposition 1.

The proof can be divided into 3 parts:

(i) To find the optimal q vector, take derivative of π_m with respect to q. We can readily derive the corresponding equilibrium solutions and they are given by

$$\pi_m(q) = (1 - 11'q) \circ q - (w_x + w_y + 1 - c_m + \phi\xi) \circ q$$

From backward induction, to find the optimal q_i for the manufacturer follower, we take derivative of π_m with respect to q_i. Drawing from the first-order condition, we can readily derive the corresponding equilibrium solution

$$\frac{\partial}{\partial q} \circ \pi_m = 1 - (\mathrm{I} + 11')q - (w_x + w_y + 1 - c_m + \phi\xi) = 0,$$
$$(\mathrm{I} + 11')q^* = -(w_x + w_y - c_m + \phi\xi) = 0.$$

Let $\mathcal{I} := (\mathrm{I}+11')^{-1}$. The solution satisfies the following fixed-point equation

$$q^* = -\mathcal{I}(w_x + w_y - c_m + \phi\xi), \tag{1}$$

The optimal solution exits and is unique since the Hessian is negatively definite, i.e., $\frac{\partial^2}{\partial \boldsymbol{q}^2} \circ \pi_m \prec 0$.

(ii) For the intermediary supplier leaders, plug q^* into π_x and π_y and obtain the supplier profits:

$$\pi_x(w_x) = -(w_x - c_x 1 + c_x\sigma)'\mathcal{I}(w_x + w_y - c_m + \phi\xi),$$
$$\pi_y(w_y) = -(w_y - c_y\sigma + \varepsilon\sigma)'\mathcal{I}(w_x + w_y - c_m + \phi\xi).$$

The optimal solutions exit and are unique because the Hessian matrix is negatively definite. Evaluate the Nash equilibriums:

$$\frac{\partial \pi_x}{\partial w_x} = -\mathcal{I}(2w_x + w_y - c_x 1 + c_x\sigma - c_m + \phi\xi) = 0,$$
$$\frac{\partial \pi_x}{\partial w_y} = -\mathcal{I}(w_x + 2w_y - c_y\sigma + \varepsilon\sigma - c_m + \phi\xi) = 0,$$

Write the equations in matrix form

$$\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} w_x^* \\ w_y^* \end{bmatrix} = \begin{bmatrix} c_x 1 - c_x\sigma - \phi\xi + c_m \\ c_y\sigma - \varepsilon\sigma - \phi\xi + c_m \end{bmatrix}.$$

We have

$$w_x^* + w_y^* = \frac{1}{3}\Big((c_y - c_x - \varepsilon)\sigma + 2c_m + c_x 1 - 2\phi\xi\Big) \tag{2}$$

$$q^* = \frac{1}{3}\mathcal{I}\big(\varepsilon\sigma - \phi\xi - (c_y - c_x)\sigma + (c_m - c_x 1)\big), \tag{3}$$

(iii) Evaluate the social welfare

$$\mathrm{SW} = \frac{1}{3}\left(\varepsilon\sigma - \phi\xi - \left(c_y - c_x\right)\sigma + \left(c_m - c_x 1\right) + \kappa\sigma\right)\mathcal{I}\left(\varepsilon\sigma - \phi\xi - \left(c_y - c_x\right)\sigma + \left(c_m - c_x 1\right)\right).$$

Differentiate with respect to ϕ

$$\frac{\partial \mathrm{SW}}{\partial \varepsilon} = \sigma'\mathcal{I}\left(\varepsilon\sigma - \phi\xi - \left(c_y - c_x\right)\sigma + \left(c_m - c_x 1\right) + \kappa\sigma\right) + \sigma'\mathcal{I}\left(\varepsilon\sigma - \phi\xi - \left(c_y - c_x\right)\sigma + \left(c_m - c_x 1\right)\right) = 0.$$

Differentiate with respect to ε

$$\begin{bmatrix} -\mathcal{I}_{\xi\xi} & \mathcal{I}_{\xi\sigma} \\ -\mathcal{I}_{\xi\sigma} & \mathcal{I}_{\sigma\sigma} \end{bmatrix}\begin{bmatrix} \phi \\ \varepsilon \end{bmatrix} = \begin{bmatrix} \left(c_y - c_x - \frac{1}{2}\kappa\right)\mathcal{I}_{\xi\sigma} - \mathcal{I}_{\xi m} \\ \left(c_y - c_x - \frac{1}{2}\kappa\right)\mathcal{I}_{\sigma\sigma} - \mathcal{I}_{\sigma m} \end{bmatrix}.$$

The solution for the control of social welfare can be solved via the Schur complement $\mathcal{I}_{\xi\xi} - \mathcal{I}_{\xi\sigma}\mathcal{I}_{\sigma\sigma}^{-1}\mathcal{I}_{\xi\sigma}$, that is, a system of linear equations $\begin{matrix} Ax + By = w \\ Cx + Dy = v \end{matrix}$, can be rewritten as $(A - BD^{-1}C)x = w - BD^{-1}v$, $Dy = v - Cx$. Therefore $\left(-\mathcal{I}_{\xi\xi} + \mathcal{I}_{\xi\sigma}\mathcal{I}_{\sigma\sigma}^{-1}\mathcal{I}_{\xi\sigma}\right)\phi = \left(c_y - c_x - \frac{1}{2}\kappa\right)\mathcal{I}_{\xi\sigma} - \mathcal{I}_{\xi m} - \mathcal{I}_{\xi\sigma}\mathcal{I}_{\sigma\sigma}^{-1}\left(\left(c_y - c_x - \frac{1}{2}\kappa\right)\mathcal{I}_{\sigma\sigma} - \mathcal{I}_{\sigma m}\right)$ and

$$\phi = \frac{\mathcal{I}_{\xi\sigma}\mathcal{I}_{\sigma m} - \mathcal{I}_{\sigma\sigma}\mathcal{I}_{\xi m}}{\mathcal{I}_{\xi\xi}\mathcal{I}_{\sigma\sigma} - \mathcal{I}_{\xi\sigma}^{2}}$$

Similarly, apply the Schur complement again in reverse vector order,

$$\begin{bmatrix} \mathcal{I}_{\xi\sigma} & -\mathcal{I}_{\xi\xi} \\ \mathcal{I}_{\sigma\sigma} & -\mathcal{I}_{\xi\sigma} \end{bmatrix}\begin{bmatrix} \varepsilon \\ \phi \end{bmatrix} = \begin{bmatrix} \left(c_y - c_x - \frac{1}{2}\kappa\right)\mathcal{I}_{\xi\sigma} - \mathcal{I}_{\xi m} \\ \left(c_y - c_x - \frac{1}{2}\kappa\right)\mathcal{I}_{\sigma\sigma} - \mathcal{I}_{\sigma m} \end{bmatrix}$$

We have

$$\varepsilon = \left(c_y - c_x - \frac{1}{2}\kappa\right) + \frac{\mathcal{I}_{\xi\xi}\mathcal{I}_{\sigma m} - \mathcal{I}_{\xi\sigma}\mathcal{I}_{\xi m}}{\mathcal{I}_{\xi\xi}\mathcal{I}_{\sigma\sigma} - \mathcal{I}_{\sigma\sigma}^{2}}$$

Proof of Proposition 2.

The derivations are straightforward.

Proof of Proposition 3.

Let $y = \left(\varepsilon\sigma - \phi\xi + \left(c_y - c_x\right)\sigma + \left(c_x 1 - c_m\right)\right)$ and $y^- = \left(\left(c_y - c_x\right)\sigma + \left(c_x 1 - c_m\right)\right)$.

$$3\left(\mathrm{SW}^{*(2S)} - SW^{*(2S^-)}\right) = (\sigma + y)\mathcal{J}y > 0,$$

$$\frac{9}{2}\left(\pi_x^{*(2S)} - \pi_y^{*(2S)}\right) - \left(\pi_x^{*(2S^-)} - \pi_y^{*(2S^-)}\right) = y'\mathcal{J}y - y^{-\prime}\mathcal{J}y^- = tr[\sigma'\sigma] > 0,$$

$$91'(\pi_m^{*(2S)} - \pi_m^{*(2S^-)}) = 1'(\mathcal{J}y \circ \mathcal{J}y - \mathcal{J}y^- \circ \mathcal{J}y^-) = 1'(\mathcal{J}\sigma \circ \mathcal{J}\sigma) > 0.$$

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陳彥銘博士畢業於華盛頓大學系統科學與數學系，現任職於國立高雄第一科技大學運籌管理系教授。曾服務於國內外產業界多年，任教後主持多項技術性開發專案計畫。專長於最適化賽局理論與程式開發，結合多篇 SCI/SSCI 國際期刊論文的發表成果，應用在實際的產學研究之中。近年來實際執行各種產學計畫及受邀國際演講，秉持著持續性與全面性的研究，專著於物流規劃、資料探勘、穿戴裝置物聯網及綠色管理議題的研究。

許鉅秉

許教授目前為國立臺灣大學（工商管理學系）特聘教授，同時亦擔任國際「物流領域」最頂級期刊 Transportation Research Part E 主編。許教授主要研究領域包括－先進物流與供應鏈管理、綠色供應鏈管理、緊急救災物流、智慧型運輸系統、及關係管理；至今已發表超過 70 篇以上 SCI/SSCI 國際期刊論文，半數以上論文為第一／單一作者，並在全世界運輸、物流、營運管理等領域公認最頂級期刊，包括 Transportation Research Parts A, B, C, E, F, Transportation Science, and Production and Operations Management, 均有論文發表。在國內學術研究表現方面，至今曾三度獲科技部傑出研究獎、國科會吳大猷獎、傑出學者計畫、優秀年輕學者計畫等獎項。許教授畢生致力研究，研究議題跨越運輸、物流、供應鏈管理、行銷、乃至應用心理學及量子力學等，並將所研發之相關理論與方法應用於解決實務界相關問題。

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