Pricing and ordering decisions of recyclables under a sustainable supply chain management: A game-theoretic approach

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Abstract

Recently, sustainable development concept has attracted a great attention in many countries. Recycling plays a major role in sustainability by improving the waste management systems. In this study, pricing and ordering decisions of a recyclable waste are considered under a sustainable supply chain containing one collector, one separator, and one recycler. In this setting, the game-theoretic frameworks including Nash and Stackelberg models are developed to set the decisions. Finally, the obtained decisions are discussed and some results are provided. It is found that different interactions established among the members do not affect the collector's decisions. From the recycler's view, the Stackelberg game with lower prices is more preferable. It is more beneficial for the members to be established the Stackelberg game among them. The members achieve more profits by making strategies that reduce the self-price or enhance the cross-price sensitivities of the demands. Moreover, from the sustainable development perspective, the Stackelberg framework is better than the Nash structure by collecting and recycling more waste.

Keywords: Sustainability; Sustainable development; Recycling; Recyclable waste; Sustainable supply chain; Supply chain management; Manufacturing; Game theory; Decision-making; Equilibrium.

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1. Introduction

Resource depletion is a concept that refers to the consumption of a resource faster than it can be replenished [1-3]. Natural resources are including renewable and non-renewable resources [4-6]. Using these forms of resources beyond their replacement rates is the resource depletion. There are several types of resource depletion such as Aquifer depletion, soil erosion, mining for fossil fuels and minerals, pollution or contamination of resources, deforestation, slash-and-burn agricultural practices, and overconsumption [7, 8].

Brundtland [9] defined the sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The sustainable development goals adopted by all United Nations are: no poverty, good health and well-being, gender equality, affordable and clean energy, industry and innovation, sustainable cities and communities, climate action, life on land, peace and justice, zero hunger, quality education, clean water and sanitation, decent work and economic growth, reduced inequalities, responsible consumption and production, life below water, and partnerships for the goals [10]. In this view, economic, environmental, and social approaches are known as three aspects of the sustainable development [7].

Many studies have investigated the sustainable development issue (e.g., see: [11, 12]). In the last two decades, by decreasing the natural resources, recycling has been significantly considered as a practical approach to improve the sustainability by reusing the waste materials to produce different products [13-16]. This approach makes the environment friendlier, saves the energy, and reduces the greenhouse gas emissions [17, 18].

Sustainable supply chain management considers three directions of the sustainable development (i.e., environmental, economic, and social aspects) under different supply chain structures. Game theory is an approach that analyses the conflicts established among some players

[19-24]. Nowadays, this approach is extensively applied under the various sustainable supply chain structures to make decisions [25, 26].

In this research, the sustainable development concept is discussed under a supply chain structure by considering the recycling process of a waste. Most of the researches that have studied the issue of recycling by applying the game theory under a sustainable supply chain are addressed as follows:

Sheu [27] analyzed the competition between a supplier and a manufacturer who produces a recyclable product in a green supply chain, whereas Sheu and Chen [28] investigated the same problem and applied a three-stage game theory approach to solve the problem. Li and Li [29] considered the competition between two sustainable supply chains applying the game theory. Jin et al. [30] established a sustainable supply chain for recycling the plastic waste and provided some standards for it. Qiu and Huang [31] discussed the recycling concept under a closed-loop supply chain by considering a stochastic demand function. Moreover, Grimes-Casey et al. [32] investigated the collecting and recycling issues for the plastic bottles and their effects on improving the sustainability.

Nagurney and Woolley [33] and Nagurney and Nagurney [11] developed a multi-criteria decision making model to maximize the members' profits under the considered structure, where Xu et al. [34] applied a multi-criteria decision-making mechanism in order to specify the collecting rate of a product under a closed-loop supply chain.

Krikke et al. [35] analyzed the recyclability of the products. Chen and Sheu [36] used the game theory to improve the recyclability rate of a product under a sustainable supply chain. Dong et al. [12] investigated the effects of investing on the recyclability of a product under a two-echelon supply chain. Furthermore, Lu et al. [37] applied a cooperative game-theoretic framework in order to analyze the efficiency rate of a recycling industry.

Recycling of the electronic waste is known as e-cycling [38]. Nagurney and Ke [39] and Nagurney and Toyasaki [40] applied the game theory to model and analyze a problem by considering an electronic waste under a supply chain in the presence of intermediators. Kaushal and Nema [41] developed a multi-objective model in order to make decisions concerning the cost and human health risk of an electronic waste. In addition, Kaushal and Nema [42] and Kaushal et al. [43] proposed a game-theoretic model to set decisions related to an electronic waste by considering the competitive and cooperative relations among the members.

Feng et al. [44] and Yi and Liang [45] discussed the issue of the channel-selection on a sustainable supply chain. Huang et al. [46] descripted a problem with dual recycling channels, where the products are sold through a retailer in the forward channel and a third-party collects the used products in the reverse channel. Yi et al. [47] investigated the collecting process under a supply chain including the dual recycling channels, where the collector and retailer collect the used products, simultaneously. Moreover, Tang et al. [48] considered a problem in order to discuss the power battery recycling process under a supply chain with dual recycling channels.

The current study aims to investigate the sustainable development issue by establishing a novel supply chain structure with dual recycling channels including one collector, one separator, and one recycler. This research analyzes pricing and ordering decisions for a recyclable waste with different brands under the considered supply chain using the game-theoretic framework. As previously addressed, the published studies have considered one type of the recyclable waste under the various supply chain structures. To our knowledge, this research is the first one that applies the game-theoretic framework to make decisions concerning a recyclable waste with various brands under a sustainable supply chain containing dual recycling channels.

The reminder of the paper is organized as follows: In Section 2, the details of the considered research problem are provided. The game theory is applied in Section 3 to make the considered decisions. Section 4 deals with the obtained results. Also, conclusions are presented in Section 5.

2. Considered problem

In this study, pricing and ordering decisions for the recyclable waste are make under a sustainable supply chain including one collector, one separator, and one recycler. The collector collects the recyclable waste with various brands and sells them to the recycler and separator. The separator separates these materials based on their brands and sells them to the recycler.

The collector sets the price of the collected materials to the recycler and separator. The separator specifies the prices of the separated recyclables for each brand to the recycler. In turn, the recycler determines the demands for the collected and separated materials based on their prices.

The recycler can separate the collected waste himself, but he prefers to buy them separately, due to high separation cost imposed to him. In fact, the recycler purchases the unseparated materials from the collector and then separates them himself with higher separation cost in order to control the prices set by the separator. The used notation are defined as follows:

K Number of the considered brands for the collected recyclables

c_1 Unit collection cost to the collector

c_2 Unit separation cost to the separator

p_r Price of the collected waste set by the collector to the recycler

p_s Price of the collected waste set by the collector to the separator

p_i Price of the separated materials with brand i $\left(i=1,2,\ldots,K\right)$ set by separator to recycler

a_r Maximum possible demand for the unseparated recyclables

a_i Maximum possible demand for the separated recyclables with brand i $\left(i=1,2,\ldots,K\right)$

a Maximum possible demand for the recyclables ($a=a_r+\sum_{i=1}^{K}a_i$)

β Self-price sensitivity of the demands

θ Cross-price sensitivity of the demands

d_r Demand determined by the recycler to the collector for the unseparated recyclables

d_i Demand determined by the recycler to the separator for the separated recyclables with brand i $(i = 1, 2, \ldots, K)$

π_c Profit for the collector

π_s Profit for the separator

The considered assumptions are:

(1) The demand in a channel is more sensitive to the change in its own price than to total changes in the other prices, i.e., $\beta > K\theta$.

(2) As previously stated, the recycler prefers to buy the recyclables separately. Thus, the maximum possible demand for the separated materials are higher than for the unseparated materials, i.e., $a_i \geq a_r$ $(i = 1, 2, \ldots, K)$.

(3) When the recycler purchases the recyclables with a price equal to their collection cost, $(\beta - K\theta)c_1$ would be the value reduced from the demand ordered by him to the collector. Also, as he receives them with a price equal to the sum of the collection and separation costs, $(\beta - K\theta)(c_1 + c_2)$ would be the value reduced from the demands ordered by the recycler to the separator. It is expected that these reduced values are lower than the maximum possible demands, i.e., $(\beta - K\theta)c_1 \leq a_r$ and $(\beta - K\theta)(c_1 + c_2) \leq a_i$ $(i = 1, 2, \ldots, K)$.

The demands determined by the recycler to the collector and separator are formulated as follows:

$$\begin{cases} d_r = a_r - \beta p_r + \theta \sum_{j=1}^{K} p_j & (1) \\ d_i = a_i - \beta p_i + \theta \left(p_r + \sum_{j=1}^{K} p_j - p_i \right) \quad \forall i = 1, 2, \ldots, K & (2) \end{cases}$$

The profits are also formulated as follows:

$$\begin{cases} \pi_c\left(p_r, p_s\right) = \left(p_r - c_1\right) d_r + \left(p_s - c_1\right) \sum_{i=1}^{K} d_i & (3) \\ \pi_s\left(p_1, p_2, \ldots, p_K\right) = \sum_{i=1}^{K} \left(p_i - p_s - c_2\right) d_i & (4) \end{cases}$$

The following constraints are considered in order to ensure that the marginal profits and the demands are nonnegative:

$$c_1 \le p_s \le p_r \le p_i \ , \quad p_s + c_2 \le p_i \qquad \forall i = 1, 2, \ldots, K \tag{5}$$

$$d_r, d_i \ge 0 \qquad \forall i = 1, 2, \ldots, K \tag{6}$$

The constraint $p_s \le p_r$ ensures that the price set by the collector to the separator is not higher than the price set by him to the recycler. Also, from the recycler's view, the price of the unseparated materials is lower than the prices of the separated recyclables, i.e., $p_r \le p_i \left(i = 1, 2, \ldots, K\right)$.

The supply chain's members and their roles have been indicated in Figure 1.

Figure 1

3. Game-theoretic models

In this section, the game-theoretic framework is developed including Nash and Stackelberg models.

3.1. Nash game model

Consider the Nash game in which the players (supply chain's members) have the same decision power and set the prices independently and simultaneously. This game is modelled as follows:

$$\begin{cases} \max\ \pi_c\left(p_r,p_s\right)=\left(p_r-c_1\right)d_r+\left(p_s-c_1\right)\sum_{i=1}^{K}d_i \ \ s.t.\ \ c_1\le p_s\le p_r \\ \max\ \pi_s\left(p_1,p_2,\ldots,p_K\right)=\sum_{i=1}^{K}\left(p_i-p_s-c_2\right)d_i \ \ s.t.\ \ p_r\le p_i, p_s+c_2\le p_i \ \ \forall i=1,2,\ldots,K \end{cases}$$

Lemma 1. *Although, π_c is not jointly concave in p_r and p_s, it is increasing in line with p_s.*

Proof: Combining the demand functions (1) and (2) with the profit function (3), the first order partial deviations of the profit function π_c to p_r and p_s are:

$$\begin{cases} \dfrac{\partial \pi_c}{\partial p_r}=a_r-2\beta p_r+\theta\sum_{j=1}^{K}p_j+\left(\beta-K\theta\right)c_1+K\theta p_s & (7) \\ \dfrac{\partial \pi_c}{\partial p_s}=\sum_{i=1}^{K}\left[a_i-\left(\beta-\theta\right)p_i+\theta\left(p_r+\sum_{j=1}^{K}p_j\right)\right]=\sum_{i=1}^{K}d_i & (8) \end{cases}$$

The Hessian matrix is calculated as follows:

$$H_c=\begin{bmatrix} \dfrac{\partial^2\pi_c}{\partial {p_r}^2} & \dfrac{\partial^2\pi_c}{\partial p_s\partial p_r} \\ \dfrac{\partial^2\pi_c}{\partial p_r\partial p_s} & \dfrac{\partial^2\pi_c}{\partial {p_s}^2} \end{bmatrix}=\begin{bmatrix} -2\beta & K\theta \\ K\theta & 0 \end{bmatrix} \quad (9)$$

Clearly, H_c is not negative definite, and consequently, π_c is not jointly concave to p_r and p_s. Since all of the demands are nonnegative, we have: $\partial\pi_c/\partial p_s=\sum_{i=1}^{K}d_i\ge 0$ and $\partial^2\pi_c/\partial {p_s}^2=0$, i.e., π_c is increasing in line with respect to p_s. □

Regarding Lemma 1 and the considered constraints, from the collector's view, the equilibrium value of p_s is equal to p_r. Now, by substituting $p_s=p_r$ into the profit function π_c, the profit function π_c^N is calculated.

Lemma 2. π_c^N *is concave in* p_r.

Proof: The first and second order partial deviations of π_c^N with respect to p_r are:

$$\frac{d\pi_c^N}{dp_r} = a - (\beta - K\theta)\left[2p_r + \sum_{j=1}^{K} p_j - c_1\right], \quad \frac{d^2\pi_c^N}{dp_r^{\ 2}} = -2(\beta - K\theta) \tag{10}$$

The second order partial deviation is negative. So, π_c^N is concave in p_r. □

Lemma 3. π_s *is jointly concave with respect to* $p_1, p_2, \ldots, p_K$.

Proof: Combining the demand functions (1) and (2) with the profit function (4), the first order partial deviations of π_s to p_i ($i = 1,2,\ldots,K$) can be given as follows:

$$\frac{\partial \pi_s}{\partial p_i} = a_i + \theta p_r + \left[\beta - (K-1)\theta\right](p_s + c_2) - 2(\beta + \theta) p_i + 2\theta \sum_{j=1}^{K} p_j \quad \forall i = 1,2,\ldots,K \tag{11}$$

By calculating the second order partial deviations, the Hessian matrix is:

$$H_s = \left[h_{ij}\right]_{K\times K} \text{ s.t. } h_{ij} = \frac{\partial^2 \pi_s}{\partial p_j \partial p_i} = \begin{cases} -2\beta & i = j \\ 2\theta & i \neq j \end{cases} \quad \forall i, j = 1,2,\ldots,K \tag{12}$$

Define the matrices $H_s^{\ w}$ ($w = 1,2,\ldots,K$) as follows:

$$H_s^{\ w} = \left[h^w_{\ ij}\right]_{w\times w} \text{ s.t. } h^w_{\ ij} = h_{ij} \quad \forall i, j = 1,2,\ldots,w \tag{13}$$

We have:

$$\det\left(H_s^{\ w}\right) = (-2)^w (\beta + \theta)^{w-1}\left[\beta - (w-1)\theta\right] \quad \forall w = 1,2,\ldots,K \tag{14}$$

$\partial^2 \pi_s / \partial p_i^2 = -2\beta < 0$ ($i = 1,2,\ldots,K$) and from assumption $\beta > K\theta$, if w ($w = 1,2,\ldots,K$) would be odd/even, then the determinate of $H_s^{\ w}$ is negative/positive. Thus, H_s is negative definite, and as a result, π_s is jointly concave with respect to $p_1, p_2, \ldots, p_K$. □

Theorem 1. *The equilibrium prices made by the players in the Nash game are given as follows:*

$$\begin{cases} p_s^{\ N} = p_r^{\ N} = \dfrac{A_2(2c_1 - Kc_2) + \left[\beta - (K-2)\theta\right]a + (\beta - K\theta)a_r}{(\beta - K\theta)A_1} \\ p_i^{\ N} = \dfrac{2(\beta+\theta)(A_3 c_1 + 2A_2 c_2) + A_4 a + A_5 a_r + (\beta - K\theta)A_1 a_i}{2(\beta+\theta)A_1} \quad \forall i = 1,2,\ldots,K \end{cases} \tag{15}$$

where, $A_1, A_2, \ldots, A_5$ *are:*

$$A_1 = (K+4)\beta - \left(K^2 + 2K - 4\right)\theta$$

$$A_2 = (\beta - K\theta)\left[\beta - (K-1)\theta\right]$$

$$A_3 = (\beta - K\theta)\left[\beta - (K-2)\theta\right]$$

$$A_4 = \beta^2 + 8\beta\theta - \left(K^2 + 4K - 4\right)\theta^2$$

$$A_5 = (\beta - K\theta)\left[\beta - (K+2)\theta\right]$$

Proof: Setting $\partial \pi_s / \partial p_i = 0 \left(i = 1, 2, \ldots, K\right)$, we have:

$$\sum_{j=1}^{K} p_j = \frac{K\theta p_r + K\left[\beta - (K-1)\theta\right](p_s + c_2) + (a - a_r)}{2\left[\beta - (K-1)\theta\right]} \tag{16}$$

By substituting the relations (16) and $p_s = p_r$ into the first order partial deviations (10) and (11) and solving them simultaneously, relation (15) is calculated. Using the considered assumptions, one can conclude this solution holds the constraints (5) and (6). Therefore, it is feasible and would be the equilibria in the Nash game model. □

3.2. Stackelberg game model

In the Stackelberg game model, first, the collector as the leader, and then, the separator as the follower, set their prices. this game is formulated as follows:

$$\begin{cases} Level1:\ \max\ \pi_c\left(p_r, p_s\right) = \left(p_r - c_1\right)d_r + \left(p_s - c_1\right)\sum_{i=1}^{K} d_i \quad s.t.\ \ c_1 \le p_s \le p_r \\ Level2:\ \max\ \pi_s\left(p_1, p_2, \ldots, p_K\right) = \sum_{i=1}^{K}\left(p_i - p_s - c_2\right)d_i \quad s.t.\ \ p_r \le p_i, p_s + c_2 \le p_i \ \ \forall i = 1, 2, \ldots, K \end{cases}$$

From Lemma 3, the profit function π_s is jointly concave in $p_1, p_2, \ldots, p_K$. Now, given the prices set by the collector, the separator's responses are calculated.

Theorem 2. *Given the prices* p_r *and* p_s *made by the collector, the prices set by the separator are:*

$$p_i\left(p_r, p_s\right)=\frac{\theta B_1 p_r+\left[\beta-(K-1)\theta\right]^2 p_s+B_2 c_2+\theta\left(a-a_r\right)+\left[\beta-(K-1)\theta\right]a_i}{2(\beta+\theta)\left[\beta-(K-1)\theta\right]} \tag{17}$$

where, B_1 *and* B_2 *are:*

$$B_1=(K+1)\beta-\left(K^2-K-1\right)\theta$$

$$B_2=(\beta+\theta)\left[\beta-(K-1)\theta\right]$$

Proof: Regarding Lemma 3, π_s is jointly concave with respect to its prices. The relation (17) can be given solving the first order partial deviations of π_s, shown in the relation (11). □

Substituting $p_i\left(p_r, p_s\right)$ ($i=1,2,\ldots,K$) into the profit function (3), π_c^S is obtained. Now, p_r and p_s are given by maximizing π_c^S.

Lemma 4. *The profit function* π_c^S *is jointly concave in* p_r *and* p_s.

Proof: The first order partial deviations of π_c^S with respect to p_r and p_s can be calculated as follows:

$$\begin{cases}\dfrac{\partial \pi_c^S}{\partial p_r}=\dfrac{B_3 c_1+K\theta\left[\beta-(K-1)\theta\right]\left(c_2+2p_s\right)-2B_8 p_r+\theta a+\left[2\beta-(2K-1)\theta\right]a_r}{2\left[\beta-(K-1)\theta\right]} & (18)\\[2ex] \dfrac{\partial \pi_c^S}{\partial p_s}=\dfrac{K\left(\beta-K\theta\right)c_1-K\left[\beta-(K-1)\theta\right]\left(c_2+2p_s\right)+2K\theta p_r+\left(a-a_r\right)}{2} & (19)\end{cases}$$

where, $B_3, B_4, \ldots, B_8$ are:

$$B_3=(\beta-K\theta)\left[2\beta-(K-2)\theta\right]$$

$$B_4=(\beta+\theta)\left[\beta-(K-2)\theta\right]$$

$$B_5=4\beta^2-(5K-4)\beta\theta+K(K-2)\theta^2$$

$$B_6=5\beta^2-7(K-1)\beta\theta+(K-2)(2K-1)\theta^2$$

$$B_7=2\beta^3-(4K-3)\beta^2\theta+\left(2K^2-3K+3\right)\beta\theta^2-(K-2)\theta^3$$

$$B_8=2\beta^2-2(K-1)\beta\theta-K\theta^2$$

The Hessian matrix is given by calculating the second order partial deviations:

$$H_{c^S} = \begin{bmatrix} \frac{\partial^2 \pi_c^S}{\partial {p_r}^2} & \frac{\partial^2 \pi_c^S}{\partial p_s \partial p_r} \\ \frac{\partial^2 \pi_c^S}{\partial p_r \partial p_s} & \frac{\partial^2 \pi_c^S}{\partial {p_s}^2} \end{bmatrix} = \begin{bmatrix} \frac{-B_8}{\beta-(K-1)\theta} & K\theta \\ K\theta & -K\left[\beta-(K-1)\theta\right] \end{bmatrix} \tag{20}$$

Regarding the assumption $\beta > K\theta$, one can derive that $\partial^2 \pi_c^S / \partial {p_r}^2 < 0$, $\partial^2 \pi_c^S / \partial {p_s}^2 < 0$, and $\det\left(H_{c^S}\right) > 0$. Thus, H_{c^S} is negative definite and π_c^S is jointly concave to p_r and p_s. □

Theorem 3. *In the Stackelberg model, the equilibrium prices are as follows:*

$$\begin{cases} {p_s}^S = {p_r}^S = \dfrac{B_3 c_1 + K\theta\left[\beta-(K-1)\theta\right]c_2 + \theta a + \left[2\beta-(2K-1)\theta\right]a_r}{2B_3} \\ {p_i}^S = \dfrac{B_3 B_4 c_1 + B_2 B_5 c_2 + \theta B_6 a + B_7 a_r + 2\left[\beta-(K-1)\theta\right]B_3 a_i}{4(\beta+\theta)\left[\beta-(K-1)\theta\right]B_3} \quad \forall i = 1,2,\ldots,K \end{cases} \tag{21}$$

Proof: Solving the first order partial deviations (18) and (19) with respect to p_r and p_s, and substituting them into equation (17), the prices are calculated. From the considered assumptions, it is found that the relation $c_1 \le p_r < p_s \le p_i \left(i = 1,2,\ldots,K\right)$ holds among the prices. So, this solution does not meet the constraint (5). Regarding the above explanations, the constraint (5), and the joint concavity of π_c^S with respect to p_r and p_s, one can derive that $p_s = p_r$, as a frontier condition, holds in the Stackelberg game. Now, by substituting $p_s = p_r$ into the relations (17) and (18) and solving them simultaneously with respect to p_r and $p_i \left(i = 1,2,\ldots,K\right)$, the relation (21) can be given. This solution satisfies the constraints (5) and (6). Thus, it is feasible and would be the equilibria under the Stackelberg game. □

4. Results

In this section, the equilibrium strategies given by the models are discussed and some results are provided. First, the equilibrium prices, demands, and profits are compared under the developed games.

Property 1. *The following relations hold between the prices set by the collector to the recycler and separator:*

$$p_r^{N} = p_s^{N}, \quad p_r^{S} = P_s^{S}$$

Perception 1. *The equilibrium prices made by the collector to the recycler and separator are equal under the Nash and Stackelberg models.*

Interpretation: It is shown that the prices set by the collector to the recycler and separator are equal in the Nash and Stackelberg games.

Insight 1. *Different interactions among the members do not affect the collector's decisions.*

Property 2. *The following inferences are derived for the prices given by the models:*

$$p_s^{S} \le p_s^{N}, \quad p_r^{S} \le p_r^{N}, \quad p_i^{S} \le p_i^{N} \qquad \forall i = 1, 2, \ldots, K$$

Perception 2. *The prices given by the Nash game are higher than by the Stackelberg game.*

Interpretation: When the prices are made simultaneously, the collector and separator compete with the same decision powers. Thus, to increase their profits, they set the prices in the Nash game higher than in the Stackelberg game.

Insight 2. *From the recycler's view, the Stackelberg game with lower prices is more preferable.*

Property 3. *The following relations hold among the demands obtained from the models:*

$$d_r^{N} \le d_r^{S}, \quad d_i^{N} \le d_i^{S} \qquad \forall i = 1, 2, \ldots, K$$

Perception 3. *The Nash game gives lower demands than the Stackelberg game.*

Interpretation: The demands are price sensitive. Therefore, higher prices lead to smaller demands. As a result, the inferences presented for the prices are reversed for the demands.

Insight 3. *From the sustainable development perspective, the Stackelberg framework is better than the Nash structure by collecting and recycling more waste. As a matter of fact, the sustainable development aims to sustain the environment for the next generations by making some policies that reduce the waste. In this view, the Stackelberg structure is environmentally preferable, due to collecting and recycling more waste.*

Property 4. *The following inferences are derived for the profits given by the models:*

$$\pi_c{}^N \le \pi_c{}^S, \;\; \pi_s{}^N \le \pi_s{}^S$$

Perception 4. *The Stackelberg game leads to higher profits for the members than the Nash game.*

Interpretation: Due to the significant decreasing in the demands under the Nash game, the members' profits in this game are lower than in the Stackelberg game.

Insight 4. *From the members' point of view, it is more beneficial to be established the Stackelberg game among them.*

Now, an instance is presented to illustrate the research problem. Consider a recyclable electronic waste (e.g., Motherboard or Monitor) that is generated by some manufacturers like APPLE, DELL, ACER, LENOVO, SONY. Assume a collector who collects the recyclables with various brands and sells them to a recycler and a separator. The separator separates the recyclables based on their brands and then sells them to the recycler, separately. Without loss of generality, it is assumed that the maximum possible demands for these separated recyclables are the same. In this situation, the prices and demands set by the recycler for them will be equal, obviously. The values of the parameters are summarized in Table 1. Moreover, the equilibrium decisions have been provided in Table 2.

Table 1

Table 2

Regarding Table 2, the collected waste under the Nash and Stackelberg games are equal to 173+5×121=778 and 638+5×285=2063, respectively. Obviously, the collected waste in the Stackelberg game is significantly greater than in the Nash game. Therefore, as stated previously, the Stackelberg framework is preferable from the sustainable development perspective.

Now, for the above example, the effects of some considered parameters are investigated on the equilibrium decisions given by the models.

We change the self-price sensitivity of the demands, i.e., β, from 2.6 to 3.4 in step sizes of 0.2. The changes in the equilibrium decisions with β are shown in Figure 2.

Figure 2

Perception 5. *Higher the self-price sensitivity of the demands leads to lower values for all of the equilibrium prices, demands, and profits given by the models.*

Interpretation: β is the demand reduced from a channel by increasing the price in this channel by one unit. A portion of this reduced demand is added to the other demands, i.e., $K\theta$, and rest, i.e., $\beta - K\theta$, is reduced from the total demand ordered by the recycler in the channels. By increasing β, the members set the prices low to decrease the demand reduced from their channels. Also, increasing β decreases the demand ordered by the recycler, clearly. Thus, the profits are also reduced by decreasing the prices and demands.

Finally, the cross-price sensitivity of the demands, i.e., θ, is changed from 0.1 to 0.5 in step sizes of 0.1. Changes in the equilibrium decisions with respect to θ are indicated in Figure 3.

Figure 3

Perception 6. *The higher the cross-price sensitivity of the demands, the higher values for the equilibrium prices, demands, and profits obtained from the developed games.*

Interpretation: θ is the demand added to a channel by increasing the price in another channel by one unit. Increasing θ enhances this added demand and decreases the reduced value from the total demand ordered by the recycler. Therefore, the demands are raised as θ increases. Also, the members set the prices with a lower risk, and thus, the prices set by them increase. As a result, the profits enhance by increasing the prices and demands.

Insight 5. *The members achieve more profits by making strategies that reduce the self-price or enhance the cross-price sensitivities of the demands.*

Insight 6. *Making policies that decrease the self-price or increase the cross-price sensitivities of the demands lead to improving the environmental sustainability by collecting and recycling more waste (increasing the considered demands).*

5. Conclusions

Supply chain management aims to investigate the environmental, economic, and social aspects of the sustainability in various supply chains. In this study, the environmental and economic aspects of the sustainability were discussed by considering a sustainable supply chain including the collector, separator, and recycler in order to make pricing and ordering decisions of a recyclable waste.

The collector collects the recyclables and then sells them with various brands to the recycler and separator. Then, the separator separates these recyclables based on their brands and sells them to the recycler, separately.

The collector makes the prices of the collected materials to the recycler and separator, while the separator specifies the prices of the separated recyclables for each brand to the recycler. In turn, the recycler sets the demands for the collected and separated materials based on their prices.

To price the recyclable waste under the considered structure, the game theory including the Nash and Stackelberg models was applied.

Then, the equilibrium strategies were discussed and some managerial insights were revealed. The obtained inferences are summarized as follows:

- Interactions established among the members have no effect on the collector's decisions.
- The Stackelberg structure with less prices is more beneficial from the recycler's perspective.
- The Stackelberg framework is more preferable from the sustainable development view by collecting and recycling more waste.
- It is more beneficial for the members to be established the Stackelberg game among them.
- The members gain more profits by making strategies that decrease the self-price or increase the cross-price sensitivities of the demands.
- Making policies that reduce the self-price or enhance the cross-price sensitivities of the demands lead to improving the environmental sustainability by collecting and recycling more waste.

Future research can consider different directions including: Several studies considered pricing decision as well as servicing decisions in the various supply chain structures (e.g., see: [49, 50]). This idea could be considered in the presented structure. A vast amount of the literature exists on the supply chain coordination (e.g., see: [51, 52]). The future research can investigate the various contract mechanisms to coordinate the members.

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Biography

Hamed Jafari have received BS, MS, and PhD degrees in Industrial Engineering from Guilan University, Sharif University of Technology, and Isfahan University of Technology in 2009, 2011, and 2016, respectively. His main areas of the research interest are Operational Research, Game Theory, Sustainable development, and Energy efficiency. Now, he is Assistant Professor in Isfahan University of Technology in Iran and works on the application of the game theoretical approaches on the various supply chain structures.

Figures and Tables captions

Figures and Tables

Table 1. The value of the parameters in the illustrative instance

Parameter	K	c_1	c_2	β	θ	a_r	a_i	a
Value	5	200	100	3.0	0.3	1000	1500	8500

Table 2. The results given by the models for the illustrative instance

Games	Prices		
	p_s	p_r	$p_i\left(i=1,2,\ldots,K\right)$
Nash	718.64	718.64	885.88
Stackelberg	500.00	500.00	758.33
	Demands		
	d_r		$d_i\left(i=1,2,\ldots,K\right)$
Nash	173		121
Stackelberg	638		285
	Profits		
	π_c		π_s
Nash	403487.50		40680.84
Stackelberg	618750.00		225625.00

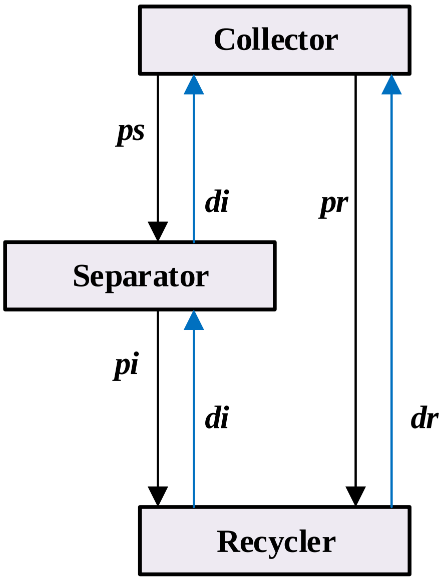

Figure 1. The supply chain's members and their roles

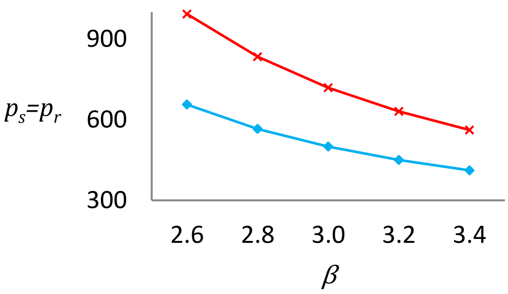

Figure 2(a). Changes of $p_s = p_r$ with β

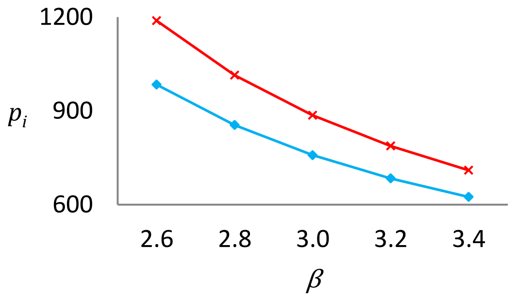

Figure 2(b). Changes of p_i with β

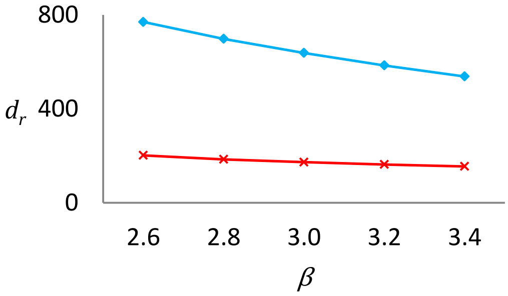

Figure 2(c). Changes of d_r with β

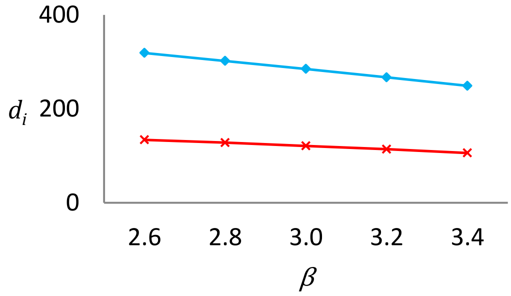

Figure 2(d). Changes of d_i with β

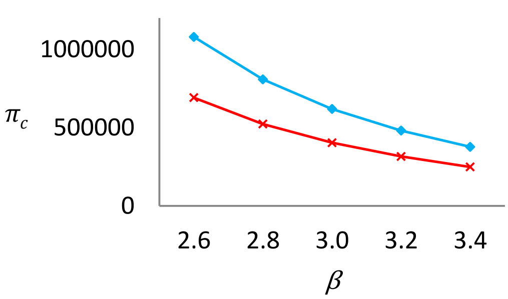

Figure 2(e). Changes of π_c with β

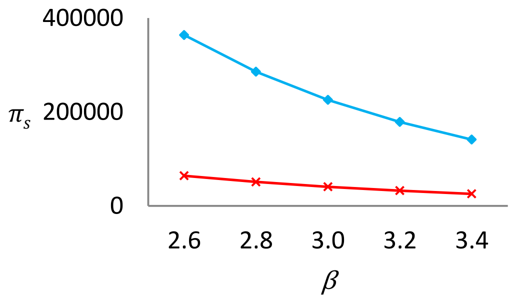

Figure 2(f). Changes of π_s with β

Figure 2. Sensitivity analysis of the self-price sensitivity of the demands

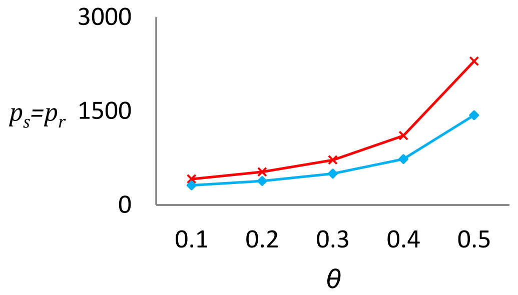

Figure 3(a). Changes of $p_s = p_r$ with θ

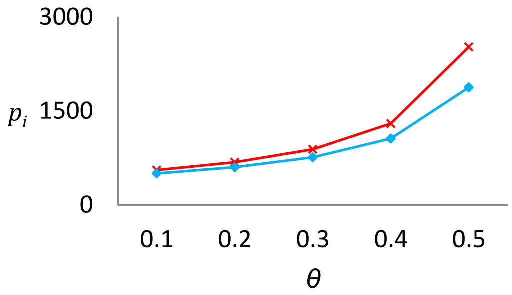

Figure 3(b). Changes of p_i with θ

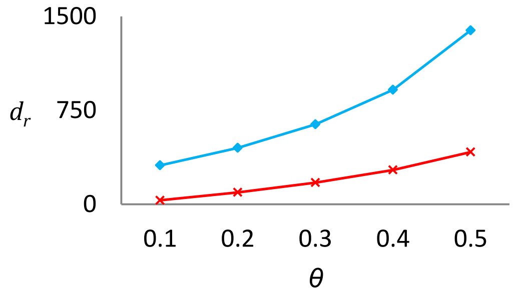

Figure 3(c). Changes of d_r with θ

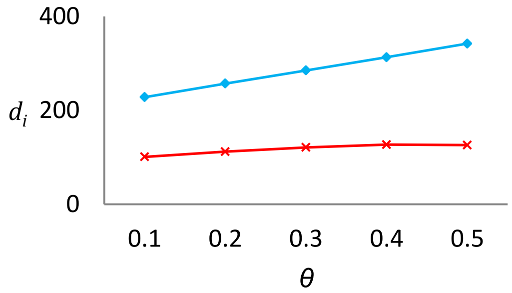

Figure 3(d). Changes of d_i with θ

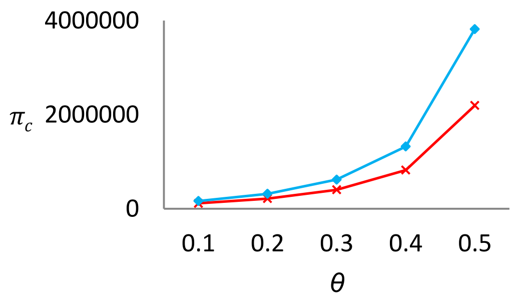

Figure 3(e). Changes of π_c with θ

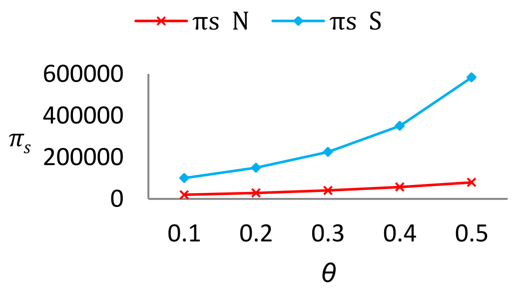

Figure 3(f). Changes of π_s with θ

Figure 3. Sensitivity analysis of the cross-price sensitivity of the demands