EFFECTS OF REVISING THE DECISIONS IN SUPPLY CHAINS

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Abstract
Real life applications reveal that the supply chain actors may revise their decisions such as the wholesale prices or selling prices, when they feel that their decisions are no longer the optimal decisions for them. Motivating from this fact, this study investigates the economic and environmental effects of revising the decisions in a closed-loop supply chain consisting of a manufacturer, a remanufacturer, and a retailer. To this end, we propose game theory based models for the cases where the actors do not have the ability of revising their decisions (Case NR) and the actors have the ability of revising the decisions (Case R). After obtaining the equilibrium decisions in both cases, we compare the decisions under various parameter settings. Computational results bring significant managerial insights regarding the economic and environmental effects of revising the decisions in supply chains.

TEDARİK ZİNCİRLERİNDE KARARLARI REVİZE ETMENİN ETKİLERİ

Anahtar Kelimeler
Tedarik Zinciri Yönetimi, Kapalı Devre Tedarik Zincirleri, Optimizasyon, Oyun Teorisi

Öz
Gerçek hayat uygulamaları, tedarik zinciri aktörlerinin, verdikleri kararların kendileri için en iyi karalar olmadığını düşündükleri durumlarda toptan ve perakende satış fiyatı gibi kararlarını revize ettiklerini göstermektedir. Bu gerçekten yola çıkarak, bu çalışma bir üretici, bir yeniden üretici ve bir perakendeciden oluşan kapalı devre bir tedarik zincirinde kararları revize edebilmenin ekonomik ve çevresel etkilerine odaklanmaktadır. Bu amaçla aktörlerin kararlarını revize etme imkanlarının olmadığı (Durum NR) ve aktörlerin kararlarını revize etme imkanlarının olduğu (Durum R) durumlara yönelik oyun teorisi temelli yaklaşımlar öne sürülmüştür. Her iki durum için de aktörlerin denge durumu kararları elde edildikten sonra, farklı parametreler altında bu kararlar birbirleri ile karşılaştırılmıştır. Hesaplama sonuçları tedarik zincirlerinde kararları revize edebilmenin ekonomik ve çevresel etkileri konusunda önemli yönetimsel bulguları beraberinde getirmiştir.

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1. Introduction

Closing the loop in a supply chain is among the well-known practices to improve the sustainability of supply chains (Banasik, Kanellopoulos, Claassen, Bloemhof-Ruwaard and van der Vorst, 2017). Existing studies reveal that in addition to a decrease in the environmental impact, companies can have 40%-65% cost reduction by conducting appropriate remanufacturing strategies (Yi, Huang, Guo and Shi, 2016). Due to this economic and environmental benefits, closed-loop supply chains have been receiving a

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growing attention in both the academia and industry (Saha, Sarmah and Moon, 2016). Real-life applications reveal that the actors may change their decisions when they feel that their decisions are no longer the best decisions for them. Motivating from this fact, in this study we investigate the economic and environmental effects of revising the decisions in supply chains. To this end, we consider a closed-loop supply chain including a manufacturer, a third-party remanufacturer and a retailer, where the manufacturer manufactures products from virgin materials and the remanufacturer collects and remanufactures the used products. Both the manufactured and remanufactured products are sold to the retailer and the retailer sells these products to customers. Manufactured and remanufactured products are assumed to be not perfect substitutes of each other and thus there is a competition between them. In addition to pricing and quantity decisions, we assume that the manufacturer and the remanufacturer have a sustainable design level decision. They may increase or decrease their sustainable design levels, which consequently yields to an increase or decrease in customer demand. In this problem setting, this study mainly focuses on the investigation of the following research question:

"What are the economic and environmental effects of revising the decisions in closed loop supply chains?"

In order to investigate this question, we consider two cases. In the first case (Case NR), we assume that once the actors make their decisions they cannot revise them, whereas in the second case (Case R), the actors can revise their decisions until they feel that they reach the optimal decisions for them. We propose game theory-based models for each of these cases and obtain the equilibrium decisions. Finally, we conduct a comprehensive computational study including several sensitivity analyses to make a comparison between these two cases under different parameter settings.

The rest of the paper is organized as follows. We discuss the related literature in the following section and present the model details in third section. Fourth section is dedicated to the analysis and equilibrium decisions and fifth section is dedicated to numerical study. Finally, we conclude in sixth section.

2. Literature Review

In this section, we present the existing literature relevant to this study in two main streams. A stream of research compares different remanufacturing systems to gain insights regarding the effect of a change in the supply chain structure or supply chain costs. For instance, Choi, Li and Xu (2013) study the performance of different channel leaderships in a closed-loop supply chain and emphasize that the remanufacturing system's efficiency is highly related to a supply chain agent's proximity to the market. Zeng (2013) present a customer segmentation model to capture consumers' different behaviors with respect to product return. The findings are expected to be used by the retailers to increase the return volume. Saha et al. (2016) compare three different collection modes for used products and state that the remanufacturing rate is maximized when the used products are collected by the manufacturer. Heydari, Govindan and Jafari (2017) consider the government grants and report that the total supply chain profit is improved through coordination with contracts and after receiving government grants. Feng, Govindan and Li (2017) examine the performances of different recycling channels and express that the dual-recycling channel always outperforms its single channel counterparts from the recyclable dealer's and system's perspectives.

Moreover, Li, Liu, Fu and Liu (2020) compare the acquisition strategies of used products in different manufacturing-remanufacturing systems and indicate that if the total cost of acquiring and remanufacturing used products does not exceed a threshold, remanufacturing can bring more profit for the manufacturer as opposed to selling only new products. Tang, Wang and Zhou (2020) study the effect of contract mechanisms in remanufacturing systems and show that a remanufacturing system can achieve the same return rate as that in the centrally coordinated channel by employing a contract between the manufacturer and the retailer. Chen, Dong, Li and He (2021) examine the cost-sharing mechanism under different power structures in a manufacturing-remanufacturing system and report that when the consumers are more satisfied with remanufactured products, the cost-sharing mechanism will reduce the profits of the members with less power. Zhou, Meng and Yuen (2021) investigate the manufacturer and remanufacturer's authorization strategies and state that authorized remanufacturing may give the manufacturer higher profit when an appropriate authorization fee is charged. Liu, Mantin and Song (2022) consider a manufacturing-remanufacturing system in which manufacturing costs of the rental and sales products differ. Based on their analysis, they report that these costs critically affect the manufacturer's renting or selling decisions. Huang, Shao, Meng, Zhang and Qiang (2022) compare the centralized and decentralized supply chains under disruptions and indicate that the centralized supply chain is better in terms of customer participation to collection process.

Another stream of research considers the environmental aspect of remanufacturing systems together with the economic aspect. For instance, Bazan, Jaber and Zanoni (2015) propose models that consider energy and carbon emissions and emphasize that energy is the main environmental cost component, thus targeting a reduction in energy usage is a priority. Bazan, Jaber and Zanoni (2017) propose models that consider energy, GHG emissions and the number of times to remanufacture (recover) a used item. Their analysis shows that incorporating these environmental costs suggest remanufacturing an item higher number of times. Chen and Akmalul'Ulya (2019) consider the greening efforts in green CLSC's and indicate that the retailer will put in more effort in greening the supply chain in the cases where the market responsiveness to his efforts is greater than that of the manufacturer. Yang, Hu and Huang (2020) study a remanufacturing system under the cap-and-trade regulation, where the collecting operations can be carried out by a manufacturer or a retailer or a third party. Their analysis reveals that when the manufacturer subjects to a stringent emission control, total carbon emissions are always the lowest in the third-party collecting mode. Yu, Bai, Xiong and Liao (2021) evaluate the greenhouse gas emissions, water consumption, and the related costs of remanufacturing lithium-ion batteries. Their analysis reveals that among the considered batteries and remanufacturing approaches, remanufacturing NCM_{111} cell with Direct Physical Recycling induces the least negative environmental impacts.

Although most of the studies in the literature assume one-time decisions for the actors, in real-life applications, supply chain actors may change their decisions once they observe that their decisions are no longer the optimal decisions. Motivating from this fact, different from the studies above, this study investigates the effects of revising the decisions in remanufacturing systems. Similar to the studies in the second stream, in this study we do not only focus on the economic aspect of the remanufacturing systems, but we also consider the environmental aspect by putting the sustainable design levels of the actors into account. To the best of our knowledge, this study is the first study in the literature, investigating the economic and environmental effects of revising the decisions in remanufacturing systems by proposing models for both cases and making a comparison between them.

3. Model Details

In this study, we consider a supply chain including a manufacturer, a remanufacturer, a retailer, and customers. The manufacturer manufactures a durable product such as household goods at a unit cost c_m. He has a sustainable design level denoted by s_m, which is an indicator of emitted CO_2 in manufacturing process. When the sustainable design level is high, the manufacturer emits less CO_2 and vice versa. Similar to Bai, Xu and Zhang (2018) we assume that the manufacturer pays $\theta_m {s_m}^2$ in order to be at sustainable design level, s_m, i.e., increasing the sustainable design level is less costly in lower sustainable design levels but brings a higher cost in higher levels. After the manufacturing process, the manufacturer sells these products to the retailer at a unit wholesale price, w_m. In this regard, we can present the manufacturer's objective function as in eq. (1).

$$\pi_M(w_m, s_m) = (w_m - c_m)d_m - \theta_m {s_m}^2 \qquad (1)$$

The remanufacturer, on the other hand, collects the end-of-use products manufactured by different manufacturers and makes the initial testing/sorting operation at a unit acquisition and testing/sorting cost, c_p. We assume that a fraction of products denoted by β_r is remanufacturable. He remanufactures these products at a unit remanufacturing cost, c_r. Similar to the manufacturer, the remanufacturer has also a sustainable design level denoted by s_r, which is an indicator of emitted CO_2 in remanufacturing process. The remanufacturer pays $\theta_r {s_r}^2$ in order to be at the sustainable design level, s_r. After the remanufacturing process, the remanufacturer sells the remanufactured products to the retailer at a unit wholesale price, w_r. In this context, retailer's objective function can be presented as in eq. (2).

$$\pi_X(w_r, s_r) = (w_r - c_r)d_r - \frac{c_p d_r}{\beta_r} - \theta_r {s_r}^2 \qquad (2)$$

Finally, the retailer sells both the manufactured products wholesaled from the manufacturer and remanufactured products wholesaled from the remanufacturer at selling prices, p_m and p_r and obtains the profit presented in eq. (3).

$$\pi_R(p_m, p_r) = (p_m - w_m)d_m + (p_r - w_r)d_r \qquad (3)$$

Similar to several existing studies, i.e., Zhang and Ren (2016), we assume that manufactured and remanufactured products compete with each other, and the customers have an environmental awareness. In this context, demand is represented by a function $d_m(p_m, p_r, s_m) = q_m - \gamma_1 p_m + \gamma_2 p_r + \gamma_3 s_m$ for manufactured products and $d_r(p_r, p_m, s_r) = q_r - \gamma_1 p_r + \gamma_2 p_m + \gamma_3 s_r$ for remanufactured products. Here, q_m and q_r are the market scales for manufactured and remanufactured products, respectively, γ_1 and γ_2 are the price coefficients and γ_3 is the customers' environmental awareness level. The demand is considered to be more sensitive to a product's own price than the competing product's price, i.e., $\gamma_1 > \gamma_2$. Moreover, we assume that $\gamma_1, \gamma_2 > \gamma_3$, i.e., customers are more sensitive to price than the environment and θ_m, θ_r are high enough to eliminate trivial solutions such as infinite investment to sustainable design, i.e., $\theta_m, \theta_r > \frac{\gamma_3}{2}$.

Considering the above-mentioned supply chain structure, we focus on two cases as follows. In the first case (Case NR), the manufacturer and remanufacturer make sequential decisions. First, the manufacturer decides on w_m and s_m values which maximize his own profit denoted by $\pi_M(w_m, s_m)$. Then, the remanufacturer decides on w_r and s_r values which maximize his own profit denoted by $\pi_X(w_r, s_r)$. Finally, the retailer decides on the p_m and p_r values which maximize his own profit denoted by $\pi_R(p_m, p_r)$.

On the other hand, in the second case (Case R), the manufacturer and the remanufacturer have the ability of revising their decisions by considering the competing actor's decisions and in the end, they reach to an equilibrium, i.e., they no longer want to revise their decisions. In this context, in this case, first the manufacturer and the remanufacturer decide on their w_m, s_m and w_r, s_r values and reach to an equilibrium. Then, the retailer decides on the p_m and p_r values that maximize his own profit.

4. Method and Analysis

Research and publication ethics were complied with in this study. This study does not focus on a real-life case study in an instutation. Hence, there is no need for any instutational or ethical approval.

In this section, we present the equilibrium decisions in Case NR and Case R, respectively.

4.1. Equilibrium Decisions for Case NR

As stated earlier, in this case, the manufacturer, the remanufacturer and the retailer make sequential decisions. We model this problem as a Stackelberg Game model. The Stackelberg Game is a strategic game in which the leader firm moves first and then the followers move sequentially. It is named after the German economist Heinrich Freiherr von Stackelberg who published Market Structure and Equilibrium in 1934, which described the model (Chung, Yang, Chiou and Yi, 2010).

We use backward induction to solve the problem. We first consider the retailer's problem and propose the following theorem regarding the optimal selling price decisions of the retailer.

Theorem 1: *In Case NR, retailer's optimal selling price decisions p_m, p_r, can be obtained as in Table 1.*

Table 1.

Retailer's Optimal Decisions in Case NR

$p_m = \dfrac{\gamma_1 q_m + \gamma_2 q_r + ({\gamma_1}^2 - {\gamma_2}^2) w_m + (\gamma_1 s_m + \gamma_2 s_r)\gamma_3}{2({\gamma_1}^2 - {\gamma_2}^2)}$
$p_r = \dfrac{\gamma_2 q_m + \gamma_1 q_r + ({\gamma_1}^2 - {\gamma_2}^2) w_r + (\gamma_2 s_m + \gamma_1 s_r)\gamma_3}{2({\gamma_1}^2 - {\gamma_2}^2)}$

Proof: Please see the Appendix.

After determining the optimal selling prices, next, we focus on the remanufacturer's optimal wholesale price and sustainable design level decisions and present the following theorem.

Theorem 2: *In Case NR, remanufacturer's optimal wholesale price and sustainable design level decisions w_r, s_r can be determined as in Table 2.*

Table 2.

Remanufacturer's Optimal Decisions in Case NR

$w_r = \dfrac{4\gamma_1\theta_r c_p + 4\beta_r\theta_r q_r + 4\beta_r\gamma_1\theta_r c_r + 4\beta_r\gamma_2\theta_r w_m - {\gamma_3}^2 c_p - \beta_r {\gamma_3}^2 c_r}{\beta_r(8\gamma_1\theta_r - {\gamma_3}^2)}$
$s_r = \dfrac{\gamma_3\left(\beta_r q_r + \beta_r\gamma_2 w_m - \gamma_1 c_p - \beta_r\gamma_1 c_r\right)}{\beta_r(8\gamma_1\theta_r - {\gamma_3}^2)}$

Proof: Please see the Appendix.

Finally, we focus on the manufacturer's optimal wholesale price and sustainable design level decisions and present the following theorem.

Theorem 3: *In Case NR, manufacturer's optimal wholesale price and sustainable design level decisions, w_m, s_m can be obtained as follows.*

Table 3.

Manufacturer's Optimal Decisions in Case NR

$w_m = \dfrac{\begin{bmatrix} \beta_r\theta_m\theta_r\left(32\gamma_1 q_m + 16\gamma_2 q_r + 32{\gamma_1}^2 c_m - 16{\gamma_2}^2 c_m + \dfrac{16\gamma_1\gamma_2 c_p}{\beta_r} + 16\gamma_1\gamma_2 c_r\right) \\ -{\gamma_3}^2\theta_m\left(4\gamma_2 c_p + 4\beta_r q_m + 4\beta_r\gamma_1 c_m + 4\beta_r\gamma_2 c_r\right) + \beta_r{\gamma_3}^4 c_m - 8\beta_r\gamma_1{\gamma_3}^2\theta_r c_m \end{bmatrix}}{\beta_r({\gamma_3}^4 + 64{\gamma_1}^2\theta_m\theta_r - 8\gamma_1{\gamma_3}^2\theta_m - 8\gamma_1{\gamma_3}^2\theta_r - 32{\gamma_2}^2\theta_m\theta_r)}$
$s_m = \dfrac{\gamma_3\begin{bmatrix} \beta_r\theta_r(4{\gamma_2}^2 c_m - 8{\gamma_1}^2 c_m + 8\gamma_1 q_m + 4\gamma_2 q_r + 4\gamma_1\gamma_2 c_r) \\ +\beta_r{\gamma_3}^2(-q_m + \gamma_1 c_m - \gamma_2 c_r) + \gamma_2 c_p(4\gamma_1\theta_r - {\gamma_3}^2) \end{bmatrix}}{\beta_r({\gamma_3}^4 + 64{\gamma_1}^2\theta_m\theta_r - 8\gamma_1{\gamma_3}^2\theta_m - 8\gamma_1{\gamma_3}^2\theta_r - 32{\gamma_2}^2\theta_m\theta_r)}$

Proof: Please see the Appendix.

4.2. Equilibrium Decisions for Case R

In this case, different from the previous case, the manufacturer and the remanufacturer have the ability of revising their decisions based on the competing actor's decisions until a Nash Equilibrium is obtained between the manufacturer and remanufacturer. Nash Equilibrium, named after the mathematician John Forbes Nash, is a solution concept that describes a steady state condition of the game at which no player would prefer to change his strategy as that would lower his payoffs given that all other players are adhering to the prescribed strategy (Chukwudi, Udoka and Charles, 2017).

We use backward induction to solve the problem. We first consider the retailer's problem and propose the following theorem.

Theorem 4: *In Case R, retailer's optimal price decisions p_m, p_r can be obtained as follows.*

Table 4.

Retailer's Optimal Decisions in Case R

$p_m = \frac{\gamma_1 q_m + \gamma_2 q_r + (\gamma_1{}^2 - \gamma_2{}^2) w_m + (\gamma_1 s_m + \gamma_2 s_r)\gamma_3}{2(\gamma_1{}^2 - \gamma_2{}^2)}$
$p_r = \frac{\gamma_2 q_m + \gamma_1 q_r + (\gamma_1{}^2 - \gamma_2{}^2) w_r + (\gamma_2 s_m + \gamma_1 s_r)\gamma_3}{2(\gamma_1{}^2 - \gamma_2{}^2)}$

Proof: Please see the Appendix.

Next, we focus on the optimal wholesale price and sustainable design level decisions of the manufacturer and remanufacturer and propose the following theorem.

Theorem 5: *In Case R, manufacturer's optimal wholesale price and sustainable design level decisions w_m, s_m, and remanufacturer's optimal price and sustainable design level decisions w_r, s_r can be obtained as in Table 5.*

Table 5.

Manufacturer and Remanufacturer's Optimal Decisions in Case R

$w_m = \frac{\left[\begin{array}{c}\beta_r \theta_m \theta_r \left(32\gamma_1 q_m + 16\gamma_2 q_r + 32\gamma_1{}^2 c_m + \frac{16\gamma_1\gamma_2 c_p}{\beta_r} + 16\gamma_1\gamma_2 c_r\right) + \beta_r \gamma_3{}^4 c_m \\ -8\beta_r\gamma_1\gamma_3{}^2\theta_r c_m - \gamma_3{}^2\theta_m\left(4\gamma_2 c_p + 4\beta_r q_m + 4\beta_r\gamma_1 c_m + 4\beta_r\gamma_2 c_r\right)\end{array}\right]}{\beta_r(\gamma_3{}^4 + 64\gamma_1{}^2\theta_m\theta_r - 8\gamma_1\gamma_3{}^2\theta_m - 8\gamma_1\gamma_3{}^2\theta_r - 16\gamma_2{}^2\theta_m\theta_r)}$
$s_m = \frac{\gamma_3\left[\begin{array}{c}\beta_r\theta_r\left(4\gamma_2{}^2 c_m - 8\gamma_1{}^2 c_m + 8\gamma_1 q_m + 4\gamma_2 q_r + 4\gamma_1\gamma_2 c_r + \frac{4\gamma_1\gamma_2 c_p}{\beta_r}\right) \\ +\gamma_3{}^2\beta_r(-q_m + \gamma_1 c_m - \gamma_2 c_r) - \gamma_3{}^2\gamma_2 c_p\end{array}\right]}{\beta_r(\gamma_3{}^4 + 64\gamma_1{}^2\theta_m\theta_r - 8\gamma_1\gamma_3{}^2\theta_m - 8\gamma_1\gamma_3{}^2\theta_r - 16\gamma_2{}^2\theta_m\theta_r)}$

$$w_r = \frac{\begin{bmatrix} \beta_r\theta_m\theta_r\left(16\gamma_2 q_m + 32\gamma_1 q_r + 32{\gamma_1}^2 c_r + 16\gamma_1\gamma_2 c_m + \dfrac{32{\gamma_1}^2 c_p}{\beta_r}\right) + \beta_r{\gamma_3}^4 c_r + {\gamma_3}^4 c_p \\ +{\gamma_3}^2\theta_r\left(-4\gamma_1 c_p - 4\beta_r q_r - 4\beta_r\gamma_2 c_m - 4\beta_r\gamma_1 c_r\right) + \gamma_1{\gamma_3}^2\theta_m\left(-8c_p - 8\beta_r c_r\right) \end{bmatrix}}{\beta_r({\gamma_3}^4 + 64{\gamma_1}^2\theta_m\theta_r - 8\gamma_1{\gamma_3}^2\theta_m - 8\gamma_1{\gamma_3}^2\theta_r - 16{\gamma_2}^2\theta_m\theta_r)}$$

$$s_r = \frac{\gamma_3\begin{bmatrix} \beta_r\theta_m(4{\gamma_2}^2 c_r - 8{\gamma_1}^2 c_r + 4\gamma_2 q_m + 8\gamma_1 q_r + 4\gamma_1\gamma_2 c_m) - 8{\gamma_1}^2\theta_m c_p + 4{\gamma_2}^2\theta_m c_p \\ +{\gamma_3}^2\beta_r(-q_r + \gamma_1 c_r - \gamma_2 c_m) + {\gamma_3}^2\gamma_1 c_p \end{bmatrix}}{\beta_r({\gamma_3}^4 + 64{\gamma_1}^2\theta_m\theta_r - 8\gamma_1{\gamma_3}^2\theta_m - 8\gamma_1{\gamma_3}^2\theta_r - 16{\gamma_2}^2\theta_m\theta_r)}$$

Proof: Please see the Appendix.

5. Computational Study and Managerial Findings

We first create a base case problem with the parameters presented in Table 6 below. Then we extend our analysis by making various sensitivity analyses.

Table 6.

Parameter Values for the Base Case Instance

q_m	q_r	γ_1	γ_2	γ_3	β_r	θ_m	θ_r	c_m	c_r	c_p
300	200	6	3	2	0.75	5	5	6	2	1

Computational results regarding these base case instance parameters are presented in Table 7, below.

Table 7.

Computational Results

Case	d_m	d_r	w_m	w_r	p_m	p_r	s_m	s_r	π_M	π_X	π_R	π_{system}
Case NR	84.2	68.8	38.1	30.3	64.5	54.9	3.2	2.3	2653.6	1549.3	3910.5	8113,4
Case R	89.8	67.1	35.9	29.7	63.3	54.6	3.0	2.2	2640.9	1473.9	4127.3	8242,1

Computational results reveal that, the profits of both the manufacturer and the remanufacturer decrease when the manufacturer and the remanufacturer have the ability of revising their decisions. This happens since both the manufacturer and the remanufacturer decrease their wholesale prices while revising their decisions. This decrease in the wholesale prices, on one hand yields to an increase in the retailer's profit and on the other hand increases the supply chain efficiency, i.e., the systemwide profit becomes higher.

In addition to the decrease in the wholesale prices, the manufacturer and the remanufacturer also decrease the sustainable design levels to increase their competition power when they revise their decisions. Hence, revising the decisions can be considered as a threat in terms of the environment.

It should be emphasized that the analysis and insights so far are based on the base case instance parameters. In the following subsection, we extend our analysis by making a sensitivity analysis on the problem parameters to see the effects of parameters on the decisions of the actors.

5.1. Sensitivity Analysis

In order to compare two cases under different parameter settings, we increase and decrease the value of one parameter at a time by 15%, 30% and 45%, and keep the remaining parameters constant at their base case values. A summary of the computational results is presented in Table 8 below. In that Table, percentage difference refers to the difference between Case NR and R. Minimum, mean and maximum refer to the minimum value, maximum value and mean of the instances, respectively.

Table 8.

Summary of the Sensitivity Analysis

Case	d_m	d_r	w_m	w_r	p_m	p_r	s_m	s_r	π_M	π_X	π_R
Min.	2.8%	-17.7%	-26.7%	-16.3%	-4.5%	-2.9%	-28.2%	-18.3%	-7.9%	-32.3%	1.9%
Mean	9.9%	-4.5%	-9.2%	-3.7%	-2.6%	-1.0%	-10.9%	-5.1%	-1.2%	-8.8%	6.4%
Max.	25.3%	-0.7%	-2.5%	-0.5%	-0.8%	-0.2%	0.0%	0.0%	-0.1%	-1.4%	8.2%

Various inferences can be made based on Table 8. First, we observe that due to the competition between them, when the manufacturer and the remanufacturer have the ability of revising their decisions, both actors decrease the wholesale prices. Hence, as Table 8 shows, the wholesale prices in Case R never exceed the wholesale prices in Case NR. Observing this decrease in the wholesale prices, the retailer also decreases the selling prices of both manufactured and remanufactured products to sell more products. Hence, as Table 8 shows, selling prices of the manufactured and remanufactured products in Case R never exceeds the selling prices in Case NR.

Above-mentioned changes in the wholesale and selling prices significantly affect the profits of the actors as well. Since the manufacturer and the remanufacturer decrease their wholesale prices, their profits also decrease. As Table 8 reveals, the profits of the manufacturer and remanufacturer in Case R never exceed those observed in Case NR. Hence, it is possible to claim the revising the decisions never yield to an economic benefit for the manufacturer and remanufacturer. On the other hand, when we focus on the retailer's profit, we observe that revising the decisions always improve the retailer's profit. In other words, the retailer benefits from this competition between the manufacturer and the remanufacturer.

Finally, when we focus on the environmental aspect of the supply chain, we observe from Table 8 that both the manufacturer and the remanufacturer decrease the sustainable design levels when they have the ability of revising their decisions. However, this decrease is less in the sustainable design level of the remanufactured products as opposed to the sustainable design level of the manufactured products. Hence, we can conclude that, revising the decisions is harmful to the environment especially in terms of the sustainable design level of the manufactured products.

6. Overall Discussion and Conclusion

In this study, we consider a closed-loop supply chain consisting of a manufacturer, a third-party remanufacturer and a retailer, and investigate the economic and environmental effects of revising the decisions in supply chains. To this end, we focus on two cases as the actors does not have the ability of revising their decisions (Case NR) and the actors have the ability of revising their decisions (Case R). We obtain the equilibrium decisions of the actors in both cases and compare them with each other under different parameter settings. Computational results and sensitivity analysis bring important insights regarding the effect of revising the decisions.

Our analysis brings significant managerial insights regarding the effects of revising the decisions in supply chains. Particularly, we observe that giving the ability of revising the decisions significantly deteriorates the profits of the manufacturer and remanufacturer. This happens since both actors decrease their wholesale prices to increase their competition power. As a result, the retailer purchases both manufactured and remanufactured products at lower wholesale prices which significantly improves his profit. To sum up, the competition between manufacturer and remanufacturer yields to a lose-lose situation for them and affects both of them negatively. The retailer, on the other hand, benefits from this competition between the manufacturer and retailer and increase his profit. Moreover, when we focus on the environmental aspect of the supply chain, we observe that both the manufacturer and the remanufacturer significantly decrease their sustainable design levels when they revise their decisions. This is again a result of the competition between the manufacturer and remanufacturer. By decreasing their sustainable design levels, they, in fact, try to decrease their total cost and increase their competition power. All in all, our analysis indicates that giving the ability of revising the decisions is harmful to the manufacturer, remanufacturer and environment and it is beneficial only to the retailer.

Our study can be extended in various ways in the future. First, in this study we consider a supply chain in which a third-party remanufacturer remanufactures the used products. However, real-life applications reveal that different actors may enter the remanufacturing business. In this regard, consideration of the supply chain structures in which different actors such as the manufacturer, or the retailer makes remanufacturing may bring significant insights regarding those systems. Second, in this study we consider the environmental aspect of the supply chain by considering the environmental awareness of the customers. Consideration of some widely used emission policies such as carbon cap, carbon cap-and-trade or carbon tax may also bring important insights regarding the effect of revising the decisions under those policies.

Conflict of Interest

There is no conflict of interest to declare.

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Appendix

Proof of Theorem 1: Retailers profit function can be stated as $\pi_R(p_m,p_r)=(p_m-w_m)(q_m-\gamma_1 p_m+\gamma_2 p_r+\gamma_3 s_m)+(p_r-w_r)(q_r-\gamma_1 p_r+\gamma_2 p_m+\gamma_3 s_r)$. Hessian matrix for this function with respect to p_m and p_r can be obtained as $H=\begin{bmatrix}-2\gamma_1 & 2\gamma_2\\ 2\gamma_2 & -2\gamma_1\end{bmatrix}$. Since the determinant of the principal minor $(-2\gamma_1)$ is negative and the determinant of the Hessian matrix $(4{\gamma_1}^2-4{\gamma_2}^2)$ is positive, this function is jointly concave with respect to p_m and p_r. Optimal values of p_m and p_r can be obtained using the equations $\frac{\partial\pi_R(p_m,p_r)}{\partial p_m}=0$ and $\frac{\partial\pi_R(p_m,p_r)}{\partial p_r}=0$. When we jointly solve these two equations, we obtain the values of selling prices as presented in Table 1. ■

Proof of Theorem 2: Based on the retailer's selling price decisions, quantities for the manufactured and remanufactured products can be determined as $d_m=\frac{q_m+\gamma_3 s_m-\gamma_1 w_m+\gamma_2 w_r}{2}$ and $d_r=\frac{q_r+\gamma_3 s_r-\gamma_1 w_r+\gamma_2 w_m}{2}$. Hence, remanufacturer's objective function can be stated as $\pi_X(w_r,s_r)=\left(w_r-c_r-\frac{c_p}{\beta_r}\right)\left(\frac{q_r+\gamma_3 s_r-\gamma_1 w_r+\gamma_2 w_m}{2}\right)-\theta_r {s_r}^2$. Hessian matrix for this equation in terms of d_r and s_r can be obtained as $H=\begin{bmatrix}-\gamma_1 & \frac{\gamma_3}{2}\\ \frac{\gamma_3}{2} & -2\theta_r\end{bmatrix}$. Since determinant of the principal minor $(-\gamma_1)$ is negative and determinant of the hessian matrix $\left(2\gamma_1\theta_r-\frac{{\gamma_3}^2}{4}=\frac{8\gamma_1\theta_r-{\gamma_3}^2}{4}\right)$ is positive, the function $\pi_X(w_r,s_r)$ is jointly concave with respect to w_r and s_r. Optimal values of w_r and s_r can be obtained by using the equations $\frac{\partial\pi_X(w_r,s_r)}{\partial w_r}=0$ and $\frac{\partial\pi_X(w_r,s_r)}{\partial s_r}=0$. When we jointly solve these two equations, we obtain the values of w_r and s_r as presented in Table 2. ■

Proof of Theorem 3: Based on the remanufacturer's decisions demand for manufactured products can be rearranged as $\pi_M(w_m,s_m)=(w_m-c_m)\left(\frac{q_m+\gamma_3 s_m-\gamma_1 w_m+\gamma_2\left[\frac{4\gamma_1\theta_r c_p+4\beta_r\theta_r q_r+4\beta_r\gamma_1\theta_r c_r+4\beta_r\gamma_2\theta_r w_m-{\gamma_3}^2 c_p-\beta_r{\gamma_3}^2 c_r}{\beta_r(8\gamma_1\theta_r-{\gamma_3}^2)}\right]}{2}\right)-\theta_m {s_m}^2$. Hessian matrix for this equation can be obtained as $H=\begin{bmatrix}\frac{-8{\gamma_1}^2\theta_r+{\gamma_3}^2\gamma_1+4{\gamma_2}^2\theta_r}{8\gamma_1\theta_r-{\gamma_3}^2} & \frac{\gamma_3}{2}\\ \frac{\gamma_3}{2} & -2\theta_m\end{bmatrix}$. Since the determinant of the principal minor $\left(\frac{-8{\gamma_1}^2\theta_r+{\gamma_3}^2\gamma_1+4{\gamma_2}^2\theta_r}{8\gamma_1\theta_r-{\gamma_3}^2}\right)$ is negative and the determinant of the hessian matrix is positive, the function $\pi_M(w_m,s_m)$ is jointly concave with respect to w_m and s_m. Optimal values of w_m and s_m can be obtained by using the equations $\frac{\partial\pi_M(w_m,s_m)}{\partial w_m}=0$ and $\frac{\partial\pi_M(w_m,s_m)}{\partial s_m}=0$. When we jointly solve these two equations, we obtain the values of w_m and s_m as presented in Table 3. ■

Proof of Theorem 4: Similar to the Case NR, in this case retailer's profit function is $\pi_R(p_m,p_r)=(p_m-w_m)(q_m-\gamma_1 p_m+\gamma_2 p_r+\gamma_3 s_m)+(p_r-w_r)(q_r-\gamma_1 p_r+\gamma_2 p_m+\gamma_3 s_r)$ and Hessian matrix for this function with respect to p_m and p_r is $H=\begin{bmatrix}-2\gamma_1 & 2\gamma_2\\ 2\gamma_2 & -2\gamma_1\end{bmatrix}$. Since the determinant of the principal minor $(-2\gamma_1)$ is negative and the determinant of the Hessian matrix $(4{\gamma_1}^2-4{\gamma_2}^2)$ is positive, this function is jointly concave with respect to p_m and p_r. Optimal values of p_m and p_r can be obtained using the equations $\frac{\partial\pi_R(p_m,p_r)}{\partial p_m}=0$ and $\frac{\partial\pi_R(p_m,p_r)}{\partial p_r}=0$. When we jointly solve these two equations, we obtain the values of selling prices as presented in Table 4. ■

Proof of Theorem 5: In order to find the Nash equilibrium between the actors, we first focus on the remanufacturer's problem. Remanufacturer's objective function can be stated as $\pi_X(w_r, s_r) = \left(w_r - c_r - \frac{c_p}{\beta_r}\right)\left[\frac{q_r+\gamma_3 s_r-\gamma_1 w_r+\gamma_2 w_m}{2}\right] - \theta_r {s_r}^2$. Hessian matrix corresponding to this function with respect to w_r and s_r can be obtained as $H = \begin{bmatrix} -\gamma_1 & \frac{\gamma_3}{2} \\ \frac{\gamma_3}{2} & -2\theta_r \end{bmatrix}$. Since determinant of the principal minor $(-\gamma_1)$ is negative, and determinant of the hessian matrix $\left(2\gamma_1\theta_r - \frac{{\gamma_3}^2}{4} = \frac{8\gamma_1\theta_r-{\gamma_3}^2}{4}\right)$ is positive, the function $\pi_X(w_r, s_r)$ is jointly concave with respect to w_r and s_r. Optimal values of w_r and s_r can be obtained by using the equations $\frac{\partial \pi_X(w_r,s_r)}{\partial w_r} = 0$ and $\frac{\partial \pi_X(w_r,s_r)}{\partial s_r} = 0$. When we solve these two equations, we obtain the values of w_r and s_r as $w_r = \frac{4\gamma_1\theta_r c_p+4\beta_r\theta_r q_r+4\beta_r\gamma_1\theta_r c_r+4\beta_r\gamma_2\theta_r w_m-{\gamma_3}^2 c_p-\beta_r{\gamma_3}^2 c_r}{\beta_r(8\gamma_1\theta_r-{\gamma_3}^2)}$ and $s_r = \frac{\gamma_3(\beta_r q_r+\beta_r\gamma_2 w_m-\gamma_1 c_p-\beta_r\gamma_1 c_r)}{\beta_r(8\gamma_1\theta_r-{\gamma_3}^2)}$.

Moreover, manufacturer's profit function can be stated as $\pi_M(w_m, s_m) = (w_m - c_m)\left(\frac{q_m+\gamma_3 s_m-\gamma_1 w_m+\gamma_2 w_r}{2}\right) - \theta_m {s_m}^2$. Hessian matrix corresponding to this function with respect to w_m and s_m can be obtained as $H = \begin{bmatrix} -\gamma_1 & \frac{\gamma_3}{2} \\ \frac{\gamma_3}{2} & -2\theta_m \end{bmatrix}$. Since the determinant of the principal minor $(-\gamma_1)$ is negative and the determinant of the hessian matrix $\left(2\gamma_1\theta_m - \frac{{\gamma_3}^2}{4} = \frac{8\gamma_1\theta_m-{\gamma_3}^2}{4}\right)$ is positive, the function $\pi_M(w_m, s_m)$ is joint concave with respect to w_m and s_m. Optimal values of w_m and s_m can be obtained by using the equations $\frac{\partial \pi_M(w_m,s_m)}{\partial w_m} = 0$ and $\frac{\partial \pi_M(w_m,s_m)}{\partial s_m} = 0$. When we solve these two equations, we obtain $w_m = \frac{4\gamma_2\theta_m w_r+4\gamma_1\theta_m c_m+4\theta_m q_m-{\gamma_3}^2 c_m}{8\gamma_1\theta_m-{\gamma_3}^2}$ and $s_m = \frac{\gamma_3(q_m-\gamma_1 c_m+\gamma_2 w_r)}{8\gamma_1\theta_m-{\gamma_3}^2}$.

Up to know, we found four statements for four variables, w_m, w_r, s_m, s_r each of which includes other variables. When we jointly solve these four equations, we obtain the values of the decision variables as presented in Table 5.