Joint Pricing of New and Refurbished Items: Comparison of Various Closed-Loop Supply Chain Structures

Seung Ho Yoo
Sunmoon University, Tangjeong-myeon, Asan, Chungnam, 336-708, Korea
shy1228@sunmoon.ac.kr, Tel.: +82-41-530-2536; Fax: +82-41-530-2914

ABSTRACT
We investigate a joint pricing problem on new and refurbished items in a closed-loop supply chain, which consists of a manufacturer, a seller and a refurbisher. We propose six different supply chain structures considering the integration and decentralization of three supply chain processes, and we compare their different characteristics and performances. Then, we suggest the guideline for the structural changes of a supply chain by investigating additional losses and/or savings of fixed operating costs due to the integration and/or outsourcing of processes.

Keywords: Pricing; Supply Chain Structure; Refurbishing; Closed-Loop Supply Chain

INTRODUCTION
In this study, we deal with the return issues and focus on the disposition of returns, considering two common options including refurbishing for the second-market sales and scrap (we use the term “the first market” for the market for a new item and “the second market” for the market for a refurbished item). We build comprehensive supply chain models, and we will reveal the relationships between the prices of new and refurbished items in a dynamic supply chain situation. Moreover, we will introduce and compare various possible structures of a closed-loop supply chain in order to reveal their different characteristics and show which structure yields a superior supply chain performance. We additionally suggest the guideline for the structural changes by investigating additional losses and/or savings of fixed operating costs due to the integration and/or outsourcing of processes (Literature review, references, and detailed proofs of all equations and propositions are available upon request from the author).

MATHEMATICAL FORMULATION
This study investigates a closed-loop supply chain, comprising three players: (1) a manufacturer responsible for production of a new item, (2) a seller selling a new item in the first market and receiving consumer returns, and (3) a refurbisher for the second market sales of a returned item.

Consumer Behavior
Consumers’ demand for a new item is affected by price, product quality and return policy, and we also consider a channel conflict issue. The first-market demand $D_1$ is defined as:

$$D_1 = d_0 - d_1p_1 - d_2\delta_1 - d_3b - aD_2$$

(1)
where \( d_0 \) is the demand potential, \( d_1, d_2 \) and \( d_3 \) are respective coefficients, \( p_1 \) is the selling price of a new item, and \( \delta_1 \) is the gap between quality expectation \( x_0 \) and perception \( x_1 \) (\( \delta_1 = x_0 - x_1 \)).

We also consider a practical situation where the sales of higher-margin new product are cannibalized by the sales of refurbished product \( D_2 \). In Equation (1), \( \alpha \) is a cannibalization factor, defined in \([0, 1]\). On the other hand, the return behavior of consumers is jointly affected by quality and return policy like below.

\[
R = r_0 - r_1b + r_2\delta_1, \quad (2)
\]

\[
D_2 = \theta R, \quad (3)
\]

\[
M = (1 - \theta)R \quad (4)
\]

A restocking fee \( b \) negatively affects return quantity \( R \) while the gap between the quality expectation and perception \( \delta_1 \) can either increase or decrease \( R \). A part of returned items is refurbished and sold to consumers in the second market, and the rest is scrapped. The second-market demand of a refurbished product \( D_2 \) and the scrap quantity \( M \) are determined by \( \theta \), the proportion of the second-market sales among returns, defined in \([0, 1]\).

\[
\theta = t_0 + t_1(p_1 - p_2) - t_2\delta_2 \quad (5)
\]

We regard consumers evaluate the refurbished item based on the price and quality of a new item. The larger the price gap between new and refurbished items \((p_1 - p_2)\) is, the more the second-market sales \( D_2 \) \((= \theta R)\) becomes as in practice. We regard the quality perception of a refurbished item \( x_2 \) is lower than that of a new item \( x_1 \), i.e., \( \delta_2 = x_1 - x_2 \geq 0 \).

**Profits**

The manufacturer devises the terms and conditions for a supply contract of a new product while the seller offers the supply contract of a returned item to the refurbisher. We adopt a wholesale price contract. Therefore, transfer payments between supply chain members are defined as:

\[
T_1 = w_1D_1, \quad (8)
\]

\[
T_2 = w_2D_2 \quad (9)
\]

where \( T_1 \) and \( T_2 \) are the total transfer payments for the supplies of new and refurbished items, respectively, \( w_1 \) and \( w_2 \) are their unit purchase costs. Then, the manufacturer’s profit \( \Pi^m \) is defined as:

\[
\Pi^m(w_1) = T_1 - cD_1 \quad (10)
\]

where \( c \) is unit production cost of a new item.

The seller’s profit \( \Pi^s \) and the refurbisher’s profit \( \Pi^r \) are defined as:

\[
\Pi^s(p_1, w_2 | w_1) = p_1D_1 - T_1 - (p_1 - b)R + T_2 - gM, \quad (11)
\]

\[
\Pi^r(p_2 | p_1, w_1, w_2) = p_2D_2 - T_2 - uD_2 \quad (12)
\]
where $\Pi'$ consists of the first market sales $p_1D_1$, transfer payments $T_1$ and $T_2$, refund $(p_1 - b)R$, and scrap cost $gM$ where $g$ is a unit scrap cost. $\Pi'$ comprises the second market sales $p_2D_2$, transfer payment to the seller $T_2$ and refurbishing cost $uD_2$ where $u$ is a unit refurbishing cost.

**SUPPLY CHAIN MODELS**

We propose six possible closed-loop supply chain structures considering separation and integration of processes while we suppose a player with a more bargaining power integrates other process. They include (1) Case DC: pure decentralization considering a manufacturer, a seller and a refurbisher as separate economic entities, (2) Case SR: a supply chain with a seller integrating the refurbishing process, (3) Case MS: a supply chain with a manufacturer integrating the selling process, (4) Case MR-A: a supply chain where a manufacturer integrates the refurbishing process and a seller devises the supply contract of a returned item, (5) Case MR-B: a supply chain where a manufacturer integrates the refurbishing process and considers a full-refund buyback contract for returns, and (6) Case MSR: a supply chain with a manufacturer integrating overall supply chain processes.

**Case DC: Pure Decentralization**

Based on the principal-agent paradigm, we define the three-stage decision structure of Case DC involving triple marginalization of three players as:

Maximize $\Pi''(w_1)$
subject to $\Pi'(p_1, w_2 | w_1) > 0$
Maximize $\Pi'(p_2 | p_1, w_1, w_2) > 0$
Maximize $\Pi'(p_2 | p_1, w_1, w_2)$.

By solving the above problem of Case DC, we obtain the optimal solutions as follows.

$$p_2^D(p_1, w_2) = \frac{\Theta + t_1(p_1 + w_2 + u)}{2t_1},$$

$$p_1^D(w_1) = \frac{4(\Phi + d_1(w_1-u))}{2(t_1)^2 \Psi^{DC}} + \frac{2(1+\alpha)(\Phi - d_1(w_1-u))}{(1-\alpha)^2},$$

$$w_2^D(w_1) = \frac{d_1(\Theta + t_1(w_1-u))}{t_1 \Psi^{DC}} + \frac{d_1(\Theta - d_1(w_1-u))}{t_1 \Psi^{DC}},$$

where $\Phi = d_0 - d_2\delta_1 - d_3b$, $\Theta = t_0 - t_2\delta_2$, and $\Psi^{DC} = 8d_1 - (1-\alpha)^2t_1R > 0$.

**Case SR: Integration of Seller and Refurbisher**

By the integration, the profit of the seller $\Pi''$ is defined as:

$$\Pi''(p_1, p_2 | w_1) = \Pi'' + \Pi' - F'' = p_1D_1 - T_1 - (p_1 - b)R + p_2D_2 - uD_2 - gM - F''$$
where $\Pi^r$ and $\Pi'$ are in Equations (11) and (12), and $F^{sr}$ is the additional fixed operating cost of the seller, incurred due to the integration of the refurbishing process. Then, a two-stage decision structure of Case SR and its solutions are defined as:

Maximize $\Pi_m(w_1)$ (24) subject to $\Pi_p(p_1, p_2 | w_1) > 0$ (25) Maximize $\Pi_p(p_1, p_2 | w_1)$. (26)

$$p_{1SR}(w_1) = \frac{2(\Phi + d_1 w_1 - R) + (1 - \alpha) R (\Theta + t_1 (\alpha w_1 - u + g))}{\Psi_{SR}^{SR}},$$ (27)

$$p_{2SR}(w_1) = \frac{2 d_1 (\Theta + t_1 (w_1 + u - g))}{t_1 \Psi_{SR}^{SR}} + \frac{(1 + \alpha) (\Phi - d_1 w_1 - R) + (1 - \alpha) R (\alpha \Theta + t_1 (\alpha w_1 - u + g))}{\Psi_{SR}^{SR}},$$ and (28)

$$w_{1SR} = \frac{\Phi + d_1 c + R}{2 (d_1 + \alpha t_1 R)} - \frac{R (1 - \alpha) t_1 (\Phi - d_1 c - \alpha R) + (1 + \alpha) d_1 (\Theta - t_1 (c + u - g))}{4 d_1 (d_1 + \alpha t_1 R)}$$ (29)

where $\Psi_{SR}^{SR} = 4 d_1 - (1 - \alpha)^2 t_1 R > 0$. (30)

**Case MS: Integration of Manufacturer and Seller**

By the integration of the selling process, the manufacturer’s profit $\Pi^{ms}$ is defined as:

$$\Pi^{ms}(p_1, w_2) = \Pi^m + \Pi' - F^{ms} = p_1 D_1 - c D_1 - (p_1 - b) R + T_2 - g M - F^{ms}.$$ (31)

Then, the problem of Case MS and its solutions are defined below.

Maximize $\Pi^{ms}(p_1, w_2)$ (32) subject to $\Pi'(p_2, p_1, w_2) > 0$ (33) Maximize $\Pi'(p_2, p_1, w_2)$. (34)

$$p_{1MS}(p_1, w_2) = \frac{\Theta + t_1 (p_1 + w_2 + u)}{2 t_1},$$ (35)

$$p_{1MS} = \frac{4 (\Phi + d_1 c - R) + (1 - \alpha) R (\Theta + t_1 (\alpha c - u + g))}{\Psi_{MS}^{MS}},$$ and (36)

$$w_{2MS} = \frac{4 d_1 (\Theta + t_1 (c - u - g))}{t_1 \Psi_{MS}^{MS}} + \frac{2 (1 + \alpha) (\Phi - d_1 c - R) + (1 - \alpha) R (\alpha \Theta + t_1 (\alpha (c - u) + g))}{\Psi_{MS}^{MS}}$$ (37)

where $\Psi_{MS}^{MS} = \Psi_{RC}^{DC} = 8 d_1 - (1 - \alpha)^2 t_1 R > 0$ in Equation (21). (38)

**Case MR-A: Integration of Manufacturer and Refurbisher**

Similarly, the manufacturer’s profit $\Pi^{mr}$ is defined as:

$$\Pi^{mr} = \Pi^{mr}(p_2, w_1) = \Pi^m + \Pi' - F^{mr} = T_1 - c D_1 + p_2 D_2 - T_2 - u D_2 - F^{mr}$$ (39)

Then, the three-stage decision structure of Case MR-A and its solutions are defined as:
Maximize \( \Pi_{mr}(w_1) \) \hspace{1cm} (40)  
subject to  
\( \Pi(p_1, w_2 \mid w_1) > 0 \)  
(41)  
Maximize \( \Pi_{mr}(p_1, w_2 \mid w_1) \) \hspace{1cm} (42)  
subject to  
\( \Pi_{mr}(p_2 \mid p_1, w_1, w_2) > 0 \)  
(43)  
Maximize \( \Pi_{mr}(p_2 \mid p_1, w_1, w_2) \).  
(44)  

\[
p_{2}^{MR-A}(p_1, w_1, w_2) = \frac{\Theta + t_{1}(p_1 + w_2 + u + \alpha(w_1 - c))}{2t_1}, \tag{45}
\]

\[
p_{1}^{MR-A}(w_1) = \frac{4(\Phi + d_1w_1 - R) + (1 - \alpha)R(\Theta + t_1(\alpha c - u + g))}{\psi_{MR-As}}, \tag{46}
\]

\[
w_{2}^{MR-A}(w_1) = \frac{4d_1(\Theta + t_1(\alpha c - u - g))}{\psi_{MR-As}t_1} - \alpha w_1  
+ 2(1 + \alpha)(\Phi + d_1w_1 - R) + (1 - \alpha)R(\alpha \Theta + t_1(\alpha c - u + g))}{\psi_{MR-As}}, \tag{47}
\]

\[
w_1^{MR-A} = \frac{\Phi + d_1c + R}{2d_1} - \frac{(1 - \alpha)^2t_1R(\Phi - d_1c + R)}{2d_1\psi_{MR-Am}} \tag{48}
\]

\[
- \frac{2(1 - \alpha)R(4d_1 - (1 - \alpha)^2t_1R)(1 - \alpha)t_1(\Phi - d_1c) + d_1(\Theta + t_1(c - u + g))}{2d_1^2\psi_{MR-Am}}
\]

where \( \psi_{MR-As} = \psi_{DC} = \psi_{MS} = 8d_1 - (1 - \alpha)^2t_1R > 0 \), and \( \psi_{MR-Am} = 32d_1 - 5(1 - \alpha)^2t_1R > 0 \).  
(49)  
(50)  

**Case MR-B: Integration of Manufacturer and Refurbisher with a Buyback Policy**

This section considers the integration of manufacturing and refurbishing processes under a full-refund buyback contract offer of the manufacturer.

Maximize \( \Pi_{mr}(w_1) \) \hspace{1cm} (51)  
subject to  
\( \Pi(p_1 \mid w_1) > 0 \)  
(52)  
Maximize \( \Pi(p_1 \mid w_1) \) \hspace{1cm} (53)  
subject to  
\( \Pi_{mr}(p_2 \mid p_1, w_1, w_2) > 0 \)  
(54)  
Maximize \( \Pi_{mr}(p_2 \mid p_1, w_1) \).  
(55)  

\[
p_{2}^{MR-B}(p_1, w_1) = \frac{\Theta + t_{1}(p_1 + \alpha(w_1 - c) + u - g)}{2t_1}, \tag{56}
\]

\[
p_{1}^{MR-B}(w_1) = \frac{2(\Phi + d_1w_1 - R) - \alpha R(\Theta - t_1(1 + \alpha)w_1 - \alpha c + u - g))}{2(2d_1 + \alpha t_1R)}, \tag{57}
\]

\[
w_{1}^{MR-B} = w_{2}^{MR-B} \quad \frac{4(2d_1 + \alpha t_1R)(2d_1 + \alpha t_1R)(\Phi + d_1c - R) + d_1R((1 - \alpha)(\Theta - t_1(c + u - g))) + t_1c)]}{\psi_{MR-B}}  
+ t_1R \tag{58}
\]

\[
[4d_1(\Phi - R) + 2\alpha R(t_1(1 + \alpha)(\Phi + d_1c - R) + d_1(\Theta - t_1(c + u - g)))  
+ t_1R \tag{58}
\]

\[
+ \alpha^2(1 - \alpha)t_1^2R^2(\Theta + t_1(\alpha c - u + g))}{\psi_{MR-B}}
\]

where \( \psi_{MR-B} = 4d_1(4(2d_1 + \alpha t_1R) - t_1R)(d_1 + \alpha t_1R) + \alpha^2 t_1^2 R^2(4d_1 - (1 - \alpha)^2t_1R) > 0 \).  
(59)  

670111-5
Case MSR: Full Integration of Manufacturer, Seller and Refurbisher

The integrated manufacturer’s profit $\Pi_{msr}$ is defined as:

$$\Pi_{msr}(p_1, p_2) = \Pi^n + \Pi^r + \Pi^f - F_{msr} = p_1D_1 - cD_1 - (p_1 - b)R + p_2D_2 - uD_2 - gM - F_{msr}$$

(60)

The manufacturer directly determines the selling prices of new and refurbished items as follows.

Maximize $\Pi_{msr}(p_1, p_2)$.               (61)

$$p_{1,msr} = \frac{2(\Phi + d_1c - R) + (1 - \alpha)R(\Theta + t_1(ac - u + g))}{\Psi_{msr}}$$, and

$$p_{2,msr} = \frac{2d_1(\Theta + t_1(c + u - g)) + (1 + \alpha)(\Phi - d_1c - R) + (1 - \alpha)R(\alpha\Theta + t_1(ac - u + g))}{\Psi_{msr}}$$

(62)

(63)

where $\Psi_{msr} = \Psi_{sr} = 4d_1 - (1 - \alpha)^2t_1R > 0$ in Equation (29).

RESULT COMPARISON

We set the basic parameter settings for the numerical analyses as: $\alpha = 0.5$, $\delta_1 = 0$, $\delta_2 = 10$, $d_0 = 2000$, $d_1 = 0.2$, $d_2 = 1$, $d_3 = 0.05$, $r_0 = 100$, $r_1 = 0.3$, $r_2 = 0.3$, $t_0 = 1$, $t_1 = 0.0002$, $t_2 = 0.1$, $c = 1000$, $b = 100$, $g = 50$, and $u = 40$.

Performance Comparison

This section compares the characteristics and performances of six cases involving different closed-loop supply chain structures, based on the basic numerical settings, at 427 different numerical settings per each supply chain case by increasing parameters seven times in their respective ranges. We conduct post-hoc analyses using Scheffé’s method, and the results are summarized in Table 5.

We analyze the performances of supply chain cases by using Case MSR as a benchmark, in which the first-best supply chain optimum is achieved without the moral hazard and hidden actions of supply chain members.

- $p_1$ is largest in Cases MR-A and DC, but smallest in Cases MSR and MS while Case MR-A yields the largest $p_2$ and Case MSR yields the smallest $p_2$. These deviations are due to the multiple marginalization problems, resulting in overall performance differences.

- $D_1$ is largest when the manufacturer directly sells the new item (Case MS), but $D_1$ is smallest in Cases DC, SR and MR-A due to the larger $p_1$ due to the multiple marginalization issues. On the other hand, $D_2$ is largest when a supply chain member with a bargaining power integrates the refurbishing process (Cases SR and MR-B).

- $w_1$ is largest in Case MR-A but smallest in Case MR-B. On the contrary, when purchasing the returned item, $w_2$ is largest in Case MR-B but smallest in Case MR-A. These results are due to the different transactions between the manufacturer and the seller. Note that Case MR-B yields a larger supply chain profit, i.e., $\Pi_{MR-B} > \Pi_{MR-A}$ by offering a full-refund contract of
returned items so better controlling the seller’s action, i.e., \( p_1^{MR-B} < p_1^{MR-A} \), but it yields the smaller manufacturer’s profit, i.e., \((\Pi^m)^{MR-B} < (\Pi^m)^{MR-A}\).

- If we do not consider additional fixed cost \( F \) for the integration of processes, both the manufacturer and supply chain can expect the largest profits when the manufacturer integrates the selling process (Cases MSR and MS).
- On the other hand, if not considering \( F \), the profit of either the manufacturer or supply chain is smallest when the manufacturer undertakes the second-market sales while not responsible for the first-market sales (Cases MR-A and MR-B). However, the result may be different in practice if we consider the manufacturer’s expertise in the production process which can make the refurbishing process efficient (lowering the refurbishing cost \( u \)).

Table 5. Performance comparison between supply chain structures (Group: grouped by Scheffe’s method at the significance level of 0.01, N/A: not available)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_1 ) Mean</td>
<td>7,613.82</td>
<td>7,582.75</td>
<td>5,335.14</td>
<td>7,664.79</td>
<td>7,444.65</td>
<td>5,355.67</td>
</tr>
<tr>
<td>Group</td>
<td>( p_1^{MR-A} &gt; p_1^{DC} &gt; p_1^{SR} &gt; p_1^{MR-B} &gt; p_1^{MS} &gt; p_1^{MR-A} )</td>
<td>( p_1^{MR-A} &gt; p_1^{DC} &gt; p_1^{SR} &gt; p_1^{MR-B} &gt; p_1^{MS} &gt; p_1^{MR-A} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p_2 ) Mean</td>
<td>5,966.89</td>
<td>4,325.70</td>
<td>4,538.81</td>
<td>6,577.53</td>
<td>4,794.39</td>
<td>3,753.94</td>
</tr>
<tr>
<td>Group</td>
<td>( p_2^{MR-A} &gt; p_2^{DC} &gt; p_2^{MR-B} &gt; p_2^{MS} &gt; p_2^{SR} &gt; p_2^{MR-A} )</td>
<td>( p_2^{MR-A} &gt; p_2^{DC} &gt; p_2^{MR-B} &gt; p_2^{MS} &gt; p_2^{SR} &gt; p_2^{MR-A} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( w_1 ) Mean</td>
<td>5,533.84</td>
<td>5,407.94</td>
<td>N/A</td>
<td>5,642.40</td>
<td>5,363.00</td>
<td>N/A</td>
</tr>
<tr>
<td>Group</td>
<td>( w_1^{MR-A} &gt; w_1^{DC} &gt; w_1^{SR} &gt; w_1^{MR-B} )</td>
<td>( w_1^{MR-A} &gt; w_1^{DC} &gt; w_1^{SR} &gt; w_1^{MR-B} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( w_2 ) Mean</td>
<td>4,279.97</td>
<td>N/A</td>
<td>3,702.48</td>
<td>3,120.21</td>
<td>5,363.00</td>
<td>N/A</td>
</tr>
<tr>
<td>Group</td>
<td>( w_2^{MR-B} &gt; w_2^{DC} &gt; w_2^{MS} &gt; w_2^{MR-A} )</td>
<td>( w_2^{MR-B} &gt; w_2^{DC} &gt; w_2^{MS} &gt; w_2^{MR-A} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D_1 ) Mean</td>
<td>462.70</td>
<td>459.11</td>
<td>925.40</td>
<td>459.03</td>
<td>493.38</td>
<td>918.22</td>
</tr>
<tr>
<td>Group</td>
<td>( D_1^{MS} &gt; D_1^{MR-A} &gt; D_1^{MR-B} &gt; D_1^{DC} &gt; D_1^{SR} &gt; D_1^{MR-A} )</td>
<td>( D_1^{MS} &gt; D_1^{MR-A} &gt; D_1^{MR-B} &gt; D_1^{DC} &gt; D_1^{SR} &gt; D_1^{MR-A} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D_2 ) Mean</td>
<td>23.05</td>
<td>45.59</td>
<td>11.15</td>
<td>15.22</td>
<td>37.09</td>
<td>22.42</td>
</tr>
<tr>
<td>Group</td>
<td>( D_2^{SR} &gt; D_2^{MR-B} &gt; D_2^{DC} &gt; D_2^{MSR} &gt; D_2^{MR-A} &gt; D_2^{MS} )</td>
<td>( D_2^{SR} &gt; D_2^{MR-B} &gt; D_2^{DC} &gt; D_2^{MSR} &gt; D_2^{MR-A} &gt; D_2^{MS} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Pi^m ) Mean</td>
<td>2,099,132</td>
<td>2,024,895</td>
<td>3,681,096</td>
<td>2,172,936</td>
<td>1,942,531</td>
<td>3,704,515</td>
</tr>
<tr>
<td>Group</td>
<td>( (\Pi^m + F)^{MSR} &gt; (\Pi^m + F)^{MR-A} &gt; (\Pi^m + F)^{MR-B} &gt; (\Pi^m + F)^{DC} &gt; (\Pi^m + F)^{SR} &gt; (\Pi^m + F)^{MR-B} )</td>
<td>( (\Pi^m + F)^{MSR} &gt; (\Pi^m + F)^{MR-A} &gt; (\Pi^m + F)^{MR-B} &gt; (\Pi^m + F)^{DC} &gt; (\Pi^m + F)^{SR} &gt; (\Pi^m + F)^{MR-B} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Pi ) Mean</td>
<td>2,670,220</td>
<td>2,692,067</td>
<td>3,692,724</td>
<td>2,622,472</td>
<td>2,831,557</td>
<td>3,704,515</td>
</tr>
<tr>
<td>Group</td>
<td>( (\Pi + F)^{MSR} &gt; (\Pi + F)^{SR} &gt; (\Pi + F)^{MR-B} &gt; (\Pi + F)^{DC} &gt; (\Pi + F)^{MR-A} )</td>
<td>( (\Pi + F)^{MSR} &gt; (\Pi + F)^{SR} &gt; (\Pi + F)^{MR-B} &gt; (\Pi + F)^{DC} &gt; (\Pi + F)^{MR-A} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Decision Criteria for Structural Changes

There can be various types of closed-loop supply chain structures in practice, and their structures sometimes need to change in order to remain competitive and be more profitable. In this section, we demonstrate the structural change decision among six supply chain structures. To provide a guideline, we consider the fixed operating cost issues from restructuring, and we regard that a structural change needs to be profitable to both the supply chain and the focal company with a bargaining power. Based on the numerical results in the previous section, we first investigate the effects of structural changes on the profits of the supply chain and the manufacturer in Table 6. Then, we combine them to reveal the guidelines for structural changes as in Table 7 below.
Table 6. Mean profit changes by structural changes (i.e., \((\Pi_{To} + F_{To}) - (\Pi_{From} + F_{From})\)) (the superscript i: integration, s: separation, is: both integration and separation, n: not a structural change; (+): always profitable, (–): always unprofitable)

(a) Supply chain

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Case DC</th>
<th>Case SR</th>
<th>Case MS</th>
<th>Case MR-A</th>
<th>Case MR-B</th>
<th>Case MSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case DC</td>
<td></td>
<td>21,847&quot;i</td>
<td>1,022,504&quot;i</td>
<td>–47,748&quot;–</td>
<td>161,337&quot;i</td>
<td>1,034,295&quot;i</td>
<td></td>
</tr>
<tr>
<td>Case SR</td>
<td>–21,847&quot;i</td>
<td>1,000,657&quot;n</td>
<td>–69,595&quot;n</td>
<td>139,480&quot;n</td>
<td>1,012,448&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MS</td>
<td>–1,022,504&quot;i</td>
<td>–1,000,657&quot;n</td>
<td>–1,070,252&quot;n</td>
<td>–861,167&quot;n</td>
<td>11,791&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MR-A</td>
<td>47,748&quot;+&quot;</td>
<td>69,595&quot;n</td>
<td>1,070,252&quot;n</td>
<td>209,085&quot;+&quot;</td>
<td>1,082,043&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MR-B</td>
<td>–161,337&quot;i</td>
<td>–139,489&quot;is</td>
<td>861,167&quot;is</td>
<td>–209,085&quot;–&quot;</td>
<td>872,958&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MSR</td>
<td>–1,034,295&quot;i</td>
<td>–1,012,448&quot;is</td>
<td>–11,791&quot;i</td>
<td>–1,082,043&quot;is</td>
<td>–872,958&quot;is</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Manufacturer

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Case DC</th>
<th>Case SR</th>
<th>Case MS</th>
<th>Case MR-A</th>
<th>Case MR-B</th>
<th>Case MSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case DC</td>
<td></td>
<td>–74,236&quot;–&quot;</td>
<td>1,581,964&quot;i</td>
<td>73,805&quot;i</td>
<td>–156,600&quot;–&quot;</td>
<td>1,605,383&quot;i</td>
<td></td>
</tr>
<tr>
<td>Case SR</td>
<td>74,236&quot;+&quot;</td>
<td>1,656,200&quot;i</td>
<td>148,041&quot;i</td>
<td>–82,364&quot;–&quot;</td>
<td>1,679,619&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MS</td>
<td>–1,581,964&quot;s</td>
<td>–1,656,200&quot;i</td>
<td>–1,508,159&quot;s</td>
<td>–1,738,564&quot;s</td>
<td>23,419&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MR-A</td>
<td>–73,805&quot;s</td>
<td>–148,041&quot;s</td>
<td>1,508,159&quot;is-&quot;</td>
<td>–230,405&quot;–&quot;</td>
<td>1,531,579&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MR-B</td>
<td>156,600&quot;+&quot;</td>
<td>82,364&quot;is+&quot;</td>
<td>1,738,564&quot;is+&quot;</td>
<td>230,405&quot;–&quot;</td>
<td>1,761,984&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MSR</td>
<td>–1,605,383&quot;s</td>
<td>–1,679,619&quot;s</td>
<td>–23,419&quot;s</td>
<td>–1,531,579&quot;s</td>
<td>–1,761,984&quot;s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Decision criteria for structural changes (x: not suggested; the superscript i: maximum additional fixed cost allowed for process integration, s: minimum fixed cost saving needed from process separation, is–: maximum additional fixed cost allowed for integration and separation, is+: minimum fixed cost saving needed for integration and separation)

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Case DC</th>
<th>Case SR</th>
<th>Case MS</th>
<th>Case MR-A</th>
<th>Case MR-B</th>
<th>Case MSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case DC</td>
<td></td>
<td>x</td>
<td>1,022,504&quot;i</td>
<td>x</td>
<td>x</td>
<td>1,034,295&quot;i</td>
<td></td>
</tr>
<tr>
<td>Case SR</td>
<td>21,847&quot;i</td>
<td>1,656,200&quot;i</td>
<td>655,543&quot;i</td>
<td>148,041&quot;i</td>
<td>x</td>
<td>1,012,448&quot;i</td>
<td></td>
</tr>
<tr>
<td>Case MS</td>
<td>1,581,964&quot;s</td>
<td>1,656,200&quot;i</td>
<td>655,543&quot;i</td>
<td>1,508,159&quot;is-&quot;</td>
<td>1,738,564&quot;is+&quot;</td>
<td>23,419&quot;i</td>
<td></td>
</tr>
<tr>
<td>Case MR-A</td>
<td>73,805&quot;s</td>
<td>78,446&quot;i</td>
<td>148,041&quot;s</td>
<td>1,070,252&quot;s&quot;s</td>
<td>x</td>
<td>1,082,043&quot;i</td>
<td></td>
</tr>
<tr>
<td>Case MR-B</td>
<td>161,337&quot;i</td>
<td>139,489&quot;is</td>
<td>861,167&quot;is</td>
<td>x</td>
<td>872,958&quot;i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case MSR</td>
<td>1,605,383&quot;s</td>
<td>1,679,619&quot;s&quot;s</td>
<td>23,419&quot;s&quot;s</td>
<td>1,531,579&quot;s&quot;</td>
<td>1,761,984&quot;s&quot;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In this numerical example, several structural changes are not suggested, including Case DC to SR, DC to MR-A, DC to MR-B, SR to MR-B, MR-A to MR-B and MR-B to MR-A, since they always damage the profit of either the supply chain or manufacturer. Except those, all structural changes need to be considered if they satisfy the criteria of fixed cost changes in Table 7.