Closed-loop supply chain sequential pricing under collection uncertainty

Yuanjie He*
California State Polytechnic University, Pomona, USA

In a closed-loop supply chain (CLSC), forward and reverse supply chain decisions often need to be coordinated in order to improve the CLSC's economic, environmental, and social performances. This paper models the CLSC sequential pricing decisions, namely, the forward supply chain pricing decision and the reverse supply chain collection price decision. In stage one, the reverse supply chain price (or collection price) for the used product (or component) is determined. Then in stage two, based on the collected quantity and quality, the manufacturer decides the retail price in the forward supply chain. The analytical results of optimal pricing decisions are obtained for both centralized and decentralized CLSC structures. Further, the numerical examples are presented. It can be observed that the forward supply chain price sensitivity (i.e. the consumer demand price sensitivity) influences the reverse supply chain flow differently under different CLSC structure (i.e. centralized versus decentralized). In centralized CLSC, higher forward supply chain price sensitivity results in higher reverse flow; while in decentralized CLSC, the opposite is observed. Further, under both centralized and decentralized CLSC structures, the reverse supply chain price sensitivity always positively influences the supply chain profitability while the forward supply chain price sensitivity negatively influences the supply chain profitability.

* Corresponding Author. E-mail address: he@cpp.edu

I. INTRODUCTION

With the improved sustainability awareness from the consumers and the increasing regulation from governments, firms are more and more focusing on improving their operations and supply chain sustainability. This trend is also reflected by the current research publications in leading OM and SCM journals. For example, Kleindorfer, Kaylan, and Van Wassenhove (2005) summarize the sustainable operations management publications on "Production and Operations Management" into three categories - green product and process design, lean and green operations, and closed-loop supply chain management. Our paper is under the scope of closed-loop supply chain management (CLSCM) literature by specifically considering the pricing decisions in a CLSC.

This research is motivated by real world examples in different industries such as electronics industry, automobile industry, and gaming industry etc. (or, any industry with large used product market). First, in such industries, the supply of reverse supply chain has grown substantially during the last decade. One reason for such growth is that with the development in sustainable supply chain management and CLSC, many companies have built or are building their reverse supply chain programs. For example, Apple Inc. announced its recycle program including all versions of IPhones and IPads in 2014; further, in March 2015, Apple Inc. expanded its recycling program by accepting used Android phones. Another factor influencing the reverse supply chain flow is the technology innovation. With the fast growth of new technology, products' life cycle becomes shorter, thus creating the used (or relatively obsolete) products quicker than before (Georgiadis, Vlachos, and Tagaras 2006). On the other hand, the demand for refurbished and remanufactured products also shows strong growth as observed in used electronics, used car, and other markets due to the competitive pricing of such products. Hence, this paper tries to build the connection between the supply and demand of the remanufacturered products and addresses the pricing issues under the CLSC context.

There is extensive literature in the area of CLSC and also literature specifically on remanufacturing related problems. Brandenburg et al. (2014), Atasu et al. (2008), Souza (2013), and Guide and Van Wassenhove (2009) are the recent review papers on CLSC related research. In particular, Guide and Van Wassenhove (2009) categorize the CLSC literature into three areas including remanufacturing operations, remanufactured products market development issues, and product return management. Recent literature on remanufacturing operations includes Georgiadis, Vlachos, and Tagaras (2006), Yuan and Gao (2010), and Georgiadis and Vlachos (2013) etc. The market development for remanufactured products mainly focuses on the market cannibalization (Guide and Li (2010), Ferguson and Toktay (2006), and Ovchinnikov (2011) etc.). As to the product return management, researchers have been focusing on the acquisition pricing and acquisition quantity (such literature includes Guide and Van Wassenhove (2001), Galbreth and Blackburn (2006), and He (2015) etc.). Our paper contributes to the CLSC and remanufacturing literature by considering the sequential pricing issues in remanufacturing supply chain, which is related to both the market development and the acquisition management literature according to the classification in Guide and Van Wassenhove (2009) and trying to build the linkage between the two areas. One closely related work is by Karakayali, Emir-Farinas, and Akcali (2007), in which they model the decentralized collection and processing operations by determining the optimal acquisition price and selling price. Our paper extends the model in Karakayali, Emir-Farinas, and Akcali (2007) and differs by considering the collection (yield) randomness in the collection process. Specifically, our model assumes the uncertain reverse (or collection) channel yield (similar to He (2015), Galbreth and Blackburn (2006) etc.) to reflect the potential quality and logistics uncertainty in the reverse channel. In this sense, our paper is also related to the random yield literature in production operations management – interested readers may refer to Gerchak, Vickson, and Parlar (1988), and Yano and Lee (1995).

In general, the model presented in this paper continues the analytical modeling research in current CLSC literature by considering the sequential pricing decisions in the forward and reverse channels under yield uncertainty. With game theoretic approach, the optimal retail price (forward supply chain price) and the optimal collection price (reverse supply chain price) are both obtained, based on which, the numerical examples are used to demonstrate some managerial insights. It is shown that the market price sensitivity (for remanufactured products) in the forward supply chain enhances the reverse supply chain flow under the centralized structure, but reduces the reverse supply chain flow under the decentralized CLSC structure. Hence, if considering high reverse supply chain flow as the CLSC's sustainability measurement, higher forward supply chain price sensitivity improves this sustainability measurement under centralized or contract-coordinated supply chains. Without coordination, higher forward supply chain price sensitivity may negatively influence the sustainability measurement as shown in the decentralized case. On the other hand, the collection price sensitivity in the reverse supply chain affects the sustainability measurement in an opposite way by positively influencing the reverse flow in non-coordinated CLSC structure and reducing the reverse flow in coordinated CLSC structure.

At the same time, it can be noticed from our numerical examples that the lack of CLSC coordination impairs the financial performance of CLSC. Further, Higher forward supply chain price sensitivity reduces the supply chain and its parties' profits or the financial/economic performance of the CLSC; while the reverse supply chain price sensitivity improves the financial performances of the CLSC. Combining the impact of price sensitivities on both the sustainability and financial measurements, it can be observed that higher reverse supply chain price sensitivity improves both the reverse flow and the financial performance in the CLSC, resulting in the alignment between the economic and environmental goals; while higher forward supply chain price sensitivity does not necessarily incur such alignment. There have been conflicting results on whether green supply chain practices (CLSC, waste reduction, green supply chain integration, green product design etc.) bring competitive advantages or not. In general, regarding the triple bottom line (TPL) and the alignment issues among economic, environmental, and social sustainability, different results are found from the empirical and modeling research. For example, Rao and Holt (2005) find evidences from the survey data and show that green practices lead to integrated green supply chain and economic performances. With modeling approach, Jacobs and Subramanian (2012) show the competitiveness improvement from sharing the product recovery responsibility across the supply chain. On the other hand, there is also research showing that green supply chain management practices may not necessarily lead to competitive advantages. For example, Hazen, Cegielski, and Hanna (2011) collect and analyze survey data on products made from recycled materials, suggesting that some green supply chain management practices may be ineffective and may not achieve better economic performance. From this perspective, our paper contributes to the sustainable supply chain management literature by providing managerial insights on how CLSC structure may influence the alignment between economic and environmental goals.

For the rest of the paper, the supply chain structure and the model assumptions are first presented. The problem is solved with a two-stage procedure. First, the forward supply chain pricing decision (stage-two problem) is studied. Based on the optimal response of the retail pricing decision, the reverse supply chain pricing decision (stage-two problem) is analyzed. Both the centralized and decentralized models are studied. This is followed by the numerical examples. In the end, the summary and the future research directions are presented.

II. THE CENTRALIZED MODEL

Consider a manufacturer who collects used products, remanufactures or refurbishes the products, then sells the product to the market. The manufacturer determines both the collection price v and the selling price of the remanufactured/refurbished products, p, in a two-stage process. At the beginning of stage one, the manufacturer decides v. It is assumed that the collection quantity depends on the collection price, i.e. higher v results in higher yield or collection quantity; at the same time, the collection quantity is uncertain. We model the final collection quantity as $Y(v)u$, where $Y(v)$ is an increasing concave function of v

($Y'(v) \geq 0$ and $Y''(v) \leq 0$), and u follows a general distribution on support *[0,1]* with density function $g(\cdot)$ and cumulative function $G(\cdot)$. It is also assumed that $\int_0^1 ug(u)du = \tau$. *Y(v)* represents the maximum potential yield from the collection process, which is determined by the collection price *v*. *Y(v)* is assumed to be an increasing function of *v* to show the positive relationship between collection price *v* and the maximum yield *Y(v)*. The concavity of *Y(v)* shows the increasing difficulty in raising the maximum yield with collection price. *Y(v)u* represents the final collection quantity, which follows the classic stochastic yield modeling (stochastically proportional yield model, Yano and Lee 1995). At the end of stage one, the collection randomness *u* is realized as *U*. In stage two, the manufacturer decides *p* based on the stage one result and market condition. We assume that the demand is a linear function of price *p*, i.e. *D=a-bp*, where *a,b>0*. At the end of stage two, the unsold products are salvaged at *s* per unit; and each unsatisfied demand results in π as the unit penalty cost.

In order to solve this two-stage model, we use backward induction and study the stage two problem first. In stage two, the collection quantity is already observed as *Y(v)U*; hence, based on the model assumptions, the manufacturer's stage two problem is to choose the retail price *p* so as to maximize the following function.

$$\Pi[p|v,U] = p \min[a - bp, Y(v)U] + s[Y(v)U - (a - bp)]^+ - \pi[a - bp - Y(v)U]^+ \quad (1)$$

Depending on whether the realized collection yield *Y(v)U* is higher or lower than a threshold level shown in Proposition 1, the manufacturer may choose different production and pricing strategies. The following proposition describes the stage two optimal decision of the manufacturer.

Proposition 1: With high quantity collected in stage one ($\mathrm{Y(v)U} \geq \frac{\mathrm{a-sb}}{2}$), the manufacturer sets the retail price p as the monopoly price, i.e. $\mathrm{p}^* = \frac{\mathrm{a+sb}}{2\mathrm{b}}$; on the other hand, with low yield from stage one ($\mathrm{Y(v)U} < \frac{\mathrm{a-sb}}{2}$), the optimal retail price is set at $\mathrm{p}^* = \frac{\mathrm{a-Y(v)U}}{\mathrm{b}}$.

Proof of Proposition 1:

When $a - bp \leq Y(v)U$, or $U \geq \frac{a-bp}{Y(v)}$, or $p \geq \frac{a-Y(v)U}{b}$, the manufacturer's stage 2 objective function is, $\Pi[p|v,U] = p(a - bp) + s[Y(v)U - (a - bp)]$, which is a quadratic function of p. The quadratic function is maximized at $p = \frac{a+sb}{2b}$. When $a - bp > Y(v)U$, or $U < \frac{a-bp}{Y(v)}$, or $p < \frac{a-Y(v)U}{b}$, the manufacturer's stage 2 objective function is, $\Pi[p|v,U] = pY(v)U - \pi[a - bp - Y(v)U]$, which is a linear increasing function of p (as $Y(v)U + \pi b > 0$). To summarize, the manufacturer's stage 2 objective function is linearly increasing function of p when $p < \frac{a-Y(v)U}{b}$, and it is a quadratic function when $p \geq \frac{a-Y(v)U}{b}$. Hence, there are two cases depending on the parameters as shown in Figure 1.

Case 1: if $\frac{a+sb}{2b} \geq \frac{a-Y(v)U}{b}$, or $U \geq \frac{a-sb}{2Y(v)}$ (the high yield case), the manufacturer's stage 2 objective function is maximized at $p^* = \frac{a+sb}{2b}$. The maximized stage 2 objective function is $\frac{(a+sb)^2}{4b} - s[a - Y(v)U]$.

Case 2: if $\frac{a+sb}{2b} < \frac{a-Y(v)U}{b}$, or $U < \frac{a-sb}{2Y(v)}$ (the low yield case), the manufacturer's stage 2 objective function is maximized at $p^* = \frac{a-Y(v)U}{b}$. The maximize stage 2 objective function is $\frac{a-Y(v)U}{b}Y(v)U$.

This is the end of the proof for Proposition 1.

As described in Proposition 1 and Figure 1, the optimal retail pricing decision is based on the yield realization *Y(v)U* from stage one. As shown in Figure 1, there are two possible results depending on the yield realization. When the retail price p is low, $a - bp > Y(v)U$ or $p < \frac{a-Y(v)U}{b}$, in this region of p, the stage two objective function can be written as $\Pi[p] = pY(v)U - \pi[a - bp - Y(v)U]$ (the realized sales take the smaller one between *Y(v)u* and *a-bp*, in this case, *Y(v)U*), which is a linear increasing function of p. This is why in both figures in Figure 1, the stage-two objective function increases in p when $0 \leq p \leq \frac{a-Y(v)U}{b}$.

When p is greater than $\frac{a-Y(v)U}{b}$, demand (*a-bp*) is smaller than the CLSC yield realization (*Y(v)U*), therefore, $\Pi[p|v,U] = p(a - bp) + s[Y(v)U - (a - bp)]$, which is a quadratic function of p. This quadratic function is maximized at $p = \frac{a+sb}{2b}$. Thus, depending on the relationship between the quadratic function maximum $p = \frac{a+sb}{2b}$ and the boundary $p = \frac{a-Y(v)U}{b}$, the quadratic function maximum may or may not be realized.

- High yield case - this happens when $\frac{a+sb}{2b} \geq \frac{a-Y(v)U}{b}$, i.e., the quadratic function maximum is realized as shown in the left side figure in Figure 1. After rearranging the terms in this inequality, we have $U \geq \frac{a-sb}{2Y(v)}$, which means that this case happens when the yield realization is higher than the benchmark level $\frac{a-sb}{2Y(v)}$. Intuitively, high yield case is the result from over-supply of the CLSC. As the collection yield is high as compared with the expected demand from the market, the manufacturer actually benefits and may make higher profit (the realization of the quadratic function maximum).

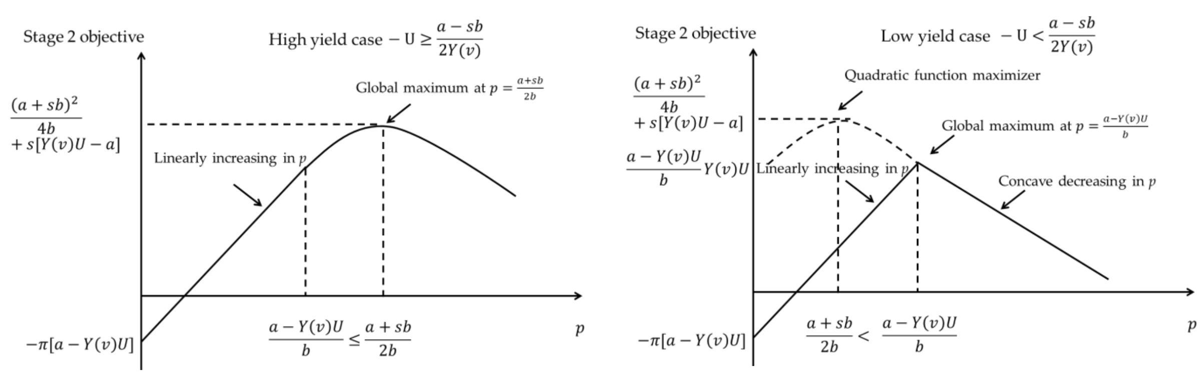

FIGURE 1. CENTRALIZED CLSC -
STAGE 2 PRICING WITH HIGH YIELD AND LOW YIELD CASES.

- Low yield case - this happens when $\frac{a+sb}{2b} < \frac{a-Y(v)U}{b}$, i.e., the quadratic function maximum is not realized as shown in the right side figure in Figure 1. And the objective function is maximized at $p = \frac{a-Y(v)U}{b}$. After rearranging the terms in this inequality, we have $U < \frac{a-sb}{2Y(v)}$, which means that this case happens when the yield realization is lower than the benchmark level $\frac{a-sb}{2Y(v)}$.

Now, knowing the stage-two response function of the forward supply chain pricing decision, and the profit function for given yield realization *U*, the manufacturer's stage one decision is the collection price *v* in order to maximize the expected manufacturer profit.

Hence, the manufacturer's stage one expected profit is,

$$\Pi[v] = \int_0^{\frac{a-sb}{2Y(v)}} \frac{a-Y(v)u}{b} Y(v)ug(u)du + \int_{\frac{a-sb}{2Y(v)}}^1 \left\{\frac{(a+sb)^2}{4b} - s[a-Y(v)u]\right\} g(u)du - vY(v)\tau \quad (2)$$

The following proposition describes the optimal collection pricing decision of the manufacturer.

Proposition 2: The manufacturer's expected profit function is concave in the collection price v if assuming that Y(v) satisfies the condition $2Y'(v) + vY''(v) \geq 0$. The optimal collection pricing decision v^* can be determined by solving,

$$\int_0^{\frac{a-sb}{2Y(v)}} [a - 2Y(v)u]ug(u)du + \int_{\frac{a-sb}{2Y(v)}}^1 sbug(u)du = \tau[Y(v) + vY'(v)]. \quad (3)$$

Proof of proposition 2:

Base on (2), taking derivative with respect to *v*, and after simplification, we have,

$$\frac{d\Pi}{dv} = \int_0^{\frac{a-sb}{2Y(v)}} [a - 2Y(v)u]ug(u)du + \int_{\frac{a-sb}{2Y(v)}}^1 sbug(u)du - \tau[Y(v) + vY'(v)]$$

Further,

$$\frac{d^2\Pi}{dv^2} = -\int_0^{\frac{a-sb}{2Y(v)}} 2Y'(v)u^2g(u)du - \tau[2Y'(v) + vY''(v)]$$

Since *Y(v)*, the maximum collection quantity, is an increasing function of collection price *v*, the first term of the above function is negative. Together with the assumption on *Y(v)*, $2Y'(v) + vY''(v) \geq 0$, $\frac{d^2\Pi}{dv^2} \leq 0$. This is the end of the proof for Proposition 2.

To summarize, with knowledge of the collection uncertainty and the stage-two response on retail pricing decisions, the manufacturer may determine the optimal collection pricing *v*. Combining the results in Proposition 1 and 2, the sequential pricing decisions in this remanufacturing/refurbishing supply chain are determined.

Further, the condition on the maximum collection quantity *Y(v)*, i.e. $2Y'(v) + vY''(v) \geq 0$, can be satisfied with some commonly used functions. For example, if assuming the linear form, i.e., $Y(v) = \alpha + \beta v$ where $,\beta > 0$, $Y'(v) = \beta$ and $Y''(v) = 0$; hence $2Y'(v) + vY''(v) = 2\beta > 0$. If assuming $Y(v) = \alpha v^\beta$, where $\alpha, \beta > 0$ and $\beta < 1$, this assumption implies the diminishing return on the maximum collection quantity $Y(v)$ from *v*. We have, $Y'(v) = \alpha\beta v^{\beta-1} > 0$ and $Y''(v) = \alpha\beta(\beta-1)v^{\beta-2} < 0$; hence, $2Y'(v) + vY''(v) = \alpha\beta(1+\beta)v^{\beta-1} > 0$.

III. THE DECENTRALIZED MODEL

In a decentralized supply chain, besides the manufacturer, there is an independent collector who is responsible for the collection process in the reverse supply chain. In stage one, the collector decides the reverse supply chain price *v*; then the yield uncertainty is realized at the end of stage one. In stage two, the (re)manufacturer decides the forward supply chain retail price p, and sell to the market. Similar to the centralized model, we solve the problem backwards.

Under this decentralized structure, we make the following assumptions. First, the information is symmetric. Hence, the manufacturer is aware of the stage one yield realization when making stage two pricing decisions, which implies that s/he does not order more than the collection yield realization, $Q \leq Y(v)U$. Also, the collector is aware of the manufacturer's cost structure and expects the manufacturer's optimal response based on the collection yield realization. Second, a wholesale price contract is applied with wholesale price *w*. As to the number of products transferred between the collector and the manufacture (*Q*), we assume that the manufacturer does not order more than the demand s/he plans to generate, i.e., $Q \leq D$ (due to the assumption $w > s$). At the same time, the manufacturer does not generate demand more than s/he plans to order from the collector, i.e., $D \leq Q$, so as to avoid unnecessary penalty cost. This implies that *D*=*Q*, or the number of product transferred between the manufacturer and the collector equals to the demand generated by the manufacturer in stage two, thus both the penalty cost and the salvage value are zero under this assumption.

Therefore, in stage two, with realized reverse supply chain yield, *Y(v)U*, the manufacturer's profit function is,

$$\Pi_M[p|v,U] = (p-w)\mathrm{Q} - \pi[D-Q]^+ + s[Q-D]^+ = (p-w)\min\,[a-bp, Y(v)U] \quad (4)$$

Similar to the stage one problem studied in the centralized CLSC, there exists a threshold level of the collection yield influencing the manufacturer pricing strategies. The following proposition describes the stage two optimal decision of the manufacturer.

Proposition 3: Under decentralized collection structure, with high collection yield in stage one $(\mathrm{Y(v)U} \geq \mathrm{a-bw})$, the manufacturer sets the retail price p as the monopoly price, i.e. $\mathrm{p^*} = \frac{\mathrm{a-bw}}{\mathrm{2b}}$; on the other hand, with low collection yield from stage one $(\mathrm{Y(v)U} < \mathrm{a-bw})$, the optimal retail price is set at $\mathrm{p^*} = \frac{\mathrm{a-Y(v)U}}{\mathrm{b}}$.

Proof of Proposition 3: Similar to the proof of Proposition 1.

Based on the manufacturer's optimal response function on the forward supply chain price, now we solve the stage one problem. In a high collection yield case when $Y(v)U \geq a-bw$, the collector expects that the manufacturer sets the monopoly price and the quantity ordered is, $Q = a-bp = \frac{a-bw}{2}$; while in a low collection yield case when $Y(v)U < a-bw$, the collector expects to deliver the realized collection yield, $Q = Y(v)U$. Therefore, the collector's expected profit based on the collection yield distribution and the response function is,

$$\Pi_{CL}[v] = w\int_0^{\frac{a-bw}{2Y(v)}} Y(v)ug(u)du + w\int_{\frac{a-bw}{2Y(v)}}^{1} \frac{a-bw}{2} g(u)du$$

$$+s\int_{\frac{a-bw}{2Y(v)}}^{1}[Y(v)u-\frac{a-bw}{2}]g(u)du-vY(v)\tau \tag{5}$$

The following proposition describes the collector's optimal reverse supply chain pricing decision under decentralized structure.

Proposition 4: The collector's expected profit function is concave in the collection price v if assuming that Y(v) satisfies the condition $2Y'(v)+(v-s)Y''(v)\geq 0$. The optimal collection pricing decision v^* can be determined by solving,

$$(w-s)\int_0^{\frac{a-bw}{2Y(v)}} Y'(v)ug(u)du=\tau[Y(v)+(v-s)Y'(v)]. \tag{6}$$

Proof of proposition 4:

Base on (5), taking derivative with respect to *v*, and after simplification, we have,

$$\frac{d\Pi_{CL}}{dv}=(w-s)\int_0^{\frac{a-bw}{2Y(v)}} Y'(v)ug(u)du - \tau[Y(v)+(v-s)Y'(v)]$$

Further,

$$\frac{d^2\Pi_{CL}}{dv^2} = (w-s)\int_0^{\frac{a-bw}{2Y(v)}} 2Y''(v)(v)ug(u)du-(w-s)\frac{(a-bw)^2[Y'(v)]^2}{4[Y(v)]^3}g(\frac{a-bw}{2Y(v)}) - \tau[2Y'(v)+(v-s)Y''(v)]$$

Since *Y(v)*, the maximum collection quantity, is an increasing concave function of collection price *v*, the first term of the above function is non-positive. The second term is negative. Then, with the assumption on *Y(v)*, $2Y'(v)+(v-s)Y''(v)\geq 0$, $\frac{d^2\Pi_{CL}}{dv^2}\leq 0$. Once again, this assumption on *Y(v)* can be satisfied with some commonly used function forms such as linear and polynomial functions. This is the end of the proof for Proposition 4.

IV. NUMERICAL EXAMPLES – IMPLICATION OF THE PRICE SENSITIVITIES

In this section, numerical examples are used to further study how the forward and reverse supply chain channels price sensitivities (*b* and *β*) affect this CLSC in its sustainability and economic goals. We first demonstrate the centralized model results in Proposition 1 and 2 with the numerical example. It is assumed that $Y(v)=\alpha+\beta v$, and *u* follows a uniform distribution on [0,1]. The following parameters are used to perform the numerical examples, a=1000, $b\in\{30,33,36,39,42,45,48\}$, $\alpha=200, \beta\in\{20,25,30,35,40\}, \pi=10, s=10$.

Figure 2 shows how the optimal collection price *v* changes with respect to the market retail and collection price sensitivities (b and β) under centralized CLSC structure. First, it can be observed that as the retail market (the forward supply chain) becomes more price sensitive (with higher *b*), the manufacturer chooses a higher collection price *v**. Further, the maximum collection quantity *Y(v)* increases as *b* increases. Both observations indicate that higher forward supply chain price sensitivity results in higher manufacturer/refurbishing quantity and encourages the reverse supply chain flows. On the other hand, when the reverse (or the collection) supply chain shows higher sensitivity indicated by higher β, *v** decreases. Therefore, the forward supply chain price sensitivity and the reverse supply chain price sensitivity influences the optimal collection price *v** differently.

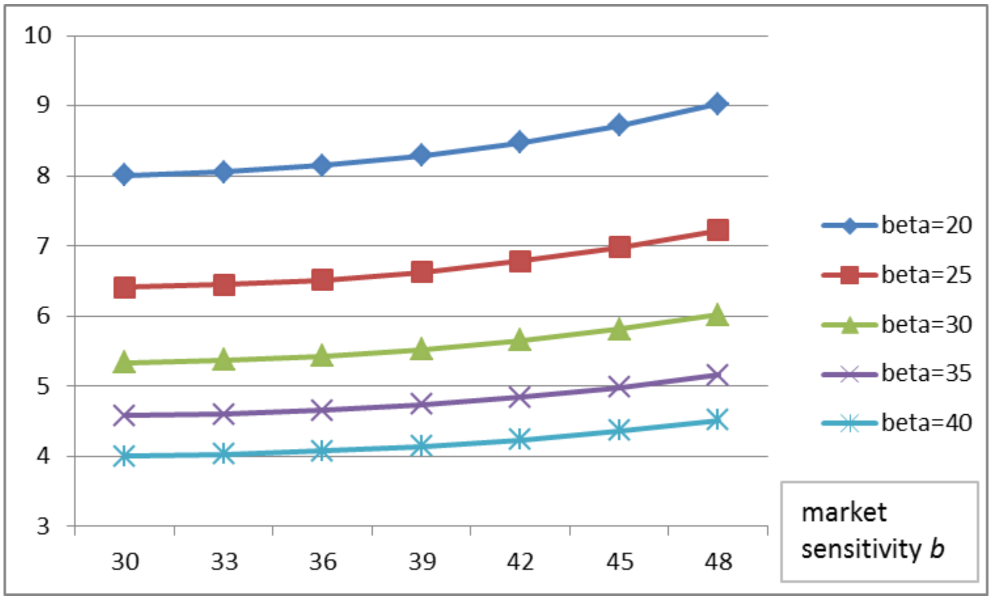

FIGURE 2. OPTIMAL COLLECTION PRICE *v IN CENTRALIZED CLSC.**

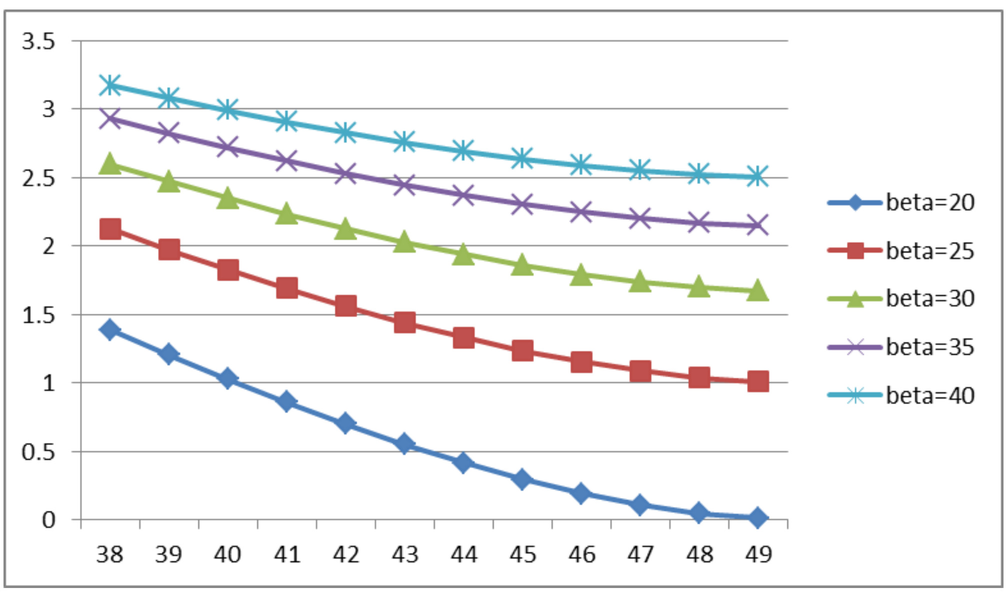

FIGURE 3. OPTIMAL COLLECTION PRICE *v IN DECENTRALIZED CLSC.**

Next, we use numerical examples to demonstrate the results from the decentralized CLSC. The following parameters are used to perform the following numerical examples, a=1000, $b \in [38,50]$, $\alpha = 200, \beta \in \{20,25,30,35,40\}, \pi = 10, s = 10$, and w = 20.

Figure 3 shows that under decentralized collection structure, as the forward supply chain price sensitivity increases, the optimal collection price decreases. Also, it can be observed that the reverse supply chain flow reduces. Hence, opposite to the observation in the centralized case, the forward supply chain price sensitivity (b) negatively impacts the company's sustainability goal. As the reverse (collection) channel price sensitivity (β) increases, it can be observed that the optimal collection price increases and the reverse supply chain flow increases – again, opposite to the observations in the centralized case.

Figure 4 demonstrates the influence of both forward and reverse supply chain price sensitivities on the manufacturer's profit under centralized CLSC structure. As shown in Figure 4, as b increases or the forward supply chain becomes more price sensitive, the manufacturer's profit (in this centralized case, same as the supply chain profit) reduces. On the other hand, as the collection or reverse supply chain becomes more price sensitive indicated by higher β, the manufacturer profit increases.

Table 1 below shows the profits of the manufacturer (Π_M), the collector (Π_{CL}), the supply chain under decentralized CLSC structure (Π_D), and the centralized CLSC (Π_C). As indicated in table 1, when b increases, the profits of the collector, the manufacturer, and the supply chain all reduce – which is similar to the observations from Figure 4. When β increases, the profits of the collector, the manufacturer, and the supply chain are all improved – similar to the centralized case. Hence, for both centralized and decentralized collection structure, the forward supply chain sensitivity generally hurts the economic performances of both parties; while the reverse supply chain price sensitivity improve the economic performances.

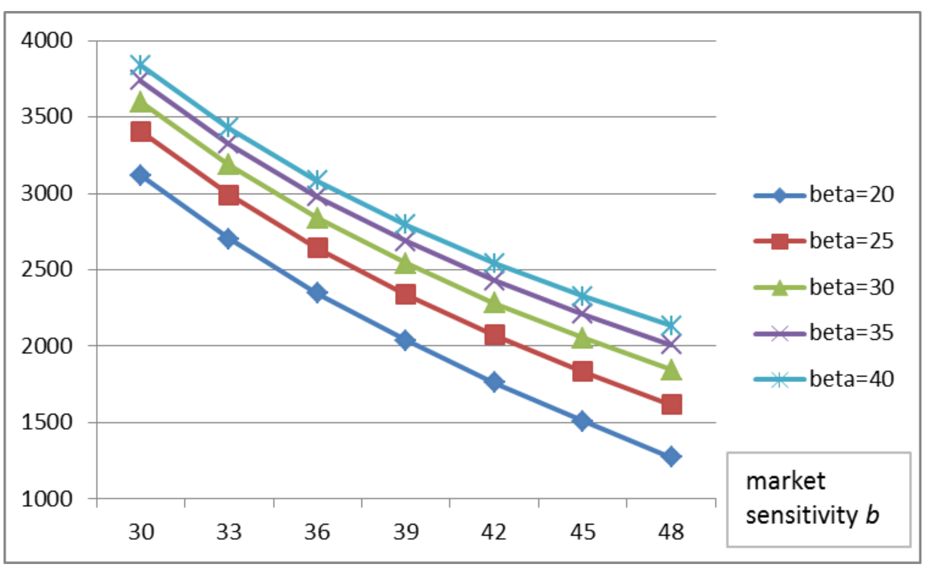

FIGURE 4. MANUFACTURER PROFITS IN CENTRALIZED CLSC.

TABLE 1. MANUFACTURER, COLLECTOR, AND SUPPLY CHAIN PROFITS UNDER DIFFERENT PRICE SENSITIVITIES

	β = 20				β = 25				β = 30			
b=	Π_{CL}	Π_M	Π_D	Π_C	Π_{CL}	Π_M	Π_D	Π_C	Π_{CL}	Π_M	Π_D	Π_C
39	1815.51	208.73	2024.24	2035.6	1858.01	219.00	2077.01	2338.7	1911.26	227.26	2138.53	2540.7
42	1645.57	114.40	1759.97	1760	1674.69	118.38	1793.07	2073.3	1717.19	121.57	1838.76	2282.1
45	1438.42	46.56	1484.98	1508.4	1457.67	47.53	1505.20	1835	1492.24	48.31	1540.55	2052.7
48	1190.02	7.78	1197.81	1273.3	1203.63	7.84	1211.47	1616.6	1233.68	7.89	1241.57	1845.5
	β = 35				β = 40							
b=	Π_{CL}	Π_M	Π_D	Π_C	Π_{CL}	Π_M	Π_D	Π_C				
39	1969.79	234.09	2203.88	2685	2031.08	239.85	2270.94	2793.2				
42	1766.84	124.21	1891.04	2431.3	1820.65	126.42	1947.07	2543.1				
45	1535.36	48.95	1584.32	2208.2	1583.71	49.49	1633.20	2324.9				
48	1273.10	7.93	1281.03	2009	1318.34	7.96	1326.31	2131.6				

Further, as shown in table 1, centralized decision making in CLSC always benefit the supply chain's financial performance as demonstrated by higher profit, i.e. $\Pi_C > \Pi_D$. And this observation agrees with the traditional supply chain coordination theories. Coordination in CLSC is also helpful for improving supply chains' financial performances. Particularly, it can be observed from this numerical example that the benefit from centralization in the studied CLSC becomes more and more significant (higher difference between Π_D and Π_C) when either the forward supply chain demand sensitivity (b) or the reverse supply chain price sensitivity (β) increases. This means that when consumer demand becomes more sensitive to the market price, CLSC managers will have higher incentive and motivation for CLSC coordination. Similarly, when the end consumer becomes more sensitive to the collection price in the recycle channel, CLSC managers will also have higher incentive for coordination.

V. CONCLUSION

The model presents the sequential pricing decisions when the manufacturer performs collection process first then goes through the retailing process, which can be commonly observed in reverse supply chain and remanufacturing business practices. Both the centralized and decentralized collection structures are studied. In general, the analytical results presented here may help managers better understand the supply chain dynamics when jointly deciding the forward and reverse supply chain prices. The numerical examples indicate different results on how forward and reverse supply chain price sensitivities influence the supply chain sustainability and economic performances in centralized and decentralized CLSC structure. Specifically, the forward supply chain price sensitivity enhances reverse supply chain flow in centralized collection structure and reduces reverse flow in decentralized structure. Also, the reverse supply chain price sensitivity reduces the reverse supply chain flow in the centralized structure and improves the flow in the decentralized structure. Another observation is that for both centralized and decentralized structures, the forward supply chain price sensitivity negatively impacts the supply chain economic goal (profits) while the reverse supply chain price sensitivity positively impacts the supply chain economic goal. Hence, when managers make pricing decisions with economic goal as the priority concern, improving reverse supply chain (collection) price sensitivity benefits all supply chain parties. On the other hand, increasing forward supply chain price sensitivity may incur misalignment between the sustainability goal and the economic goal. Based on the results of this paper, further study may be performed on designing the coordinating mechanism to improve both environmental and economic goals.

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