E-Companion: Definitions and Proofs of Technical Results

EC.1. Definitions

Below we explain the differences between pure sales, leasing, renting, and servicizing, based on the payment structure, terms of use, operating costs, and ownership, of the product.

Pure sales: The customer pays a fee to own the product and incurs operating costs.

Renting: The customer pays for short-term use of the product. The payment is based on the length of the term. The firm retains the product ownership and incurs operating costs.

Leasing: The customer pays for a medium to long-term use of the product. The payment is based on the length of the term. The firm retains the product ownership. Operating costs are either incurred by the customer or the firm based on the contract terms. One product is dedicated to each customer (Bellos et al. 2017).

Servicizing: The customer only pays for product use. The payment is based on the actual usage level of a product. The firm retains the product ownership and incurs operating costs. The firm typically does not dedicate one product to each customer (Agrawal and Bellos 2017).

EC.2. Notation

Notation	Description	Units
Parameters		
$\theta \sim U[0,1]$	Customer usage needs	hour
b	Monetary conversion parameter of usage	hour^2/dollar
c_n	Per-unit manufacturing cost of a new product	dollar/unit of product
c_r	Per-unit remanufacturing cost of previously-sold product	dollar/unit of product
c_s	Average per-unit remanufacturing cost in the presence of servicizing	dollar/unit of product
k_i	Per-use operating cost, $i \in \{n, r\}$	dollar/hour of use
δ_i	Per-unit environmental impact of manufacturing, $i \in \{n, r\}$	kg co_2 eq./unit of product
η_i	Per-use environmental impact, $i \in \{n, r\}$	kg co_2 eq./hour of use
γ	Pooling effect parameter	dimensionless
Functions		
$\Omega_i^j(p_n, p_r, k_s)$	Aggregate usage level, $i \in \{n, r, s\}$, $j \in \{N, NS, NR, NRS\}$	hour
$Q_i^j(p_n, p_r, k_s)$	Number of customers adopting product i, $i \in \{n, r, s\}$, $j \in \{N, NS, NR, NRS\}$	person
Decision Variables		
τ_i	Actual customer usage, $i \in \{n, r, s\}$	hour
p_i	Per unit selling price, $i \in \{n, r\}$	dollar/unit of product
k_s	Pay-per-use price	dollar/hour of use
Performance Metrics		
Π^j	Profit, $j \in \{N, NS, NR, NRS\}$	dollar
E^j	Environmental impact, $j \in \{N, NS, NR, NRS\}$	kg co_2 eq.

Table EC.1 Frequently Used Notation

EC.3. Product Demand

Table EC.2 summarizes the expressions for product demand as functions of prices and cost parameters under each model.

Model	Q_n	Q_r	Q_s
Model N	$1-k_n-\sqrt{2p_n^N}$	-	-
Model NS	$1-\frac{(k_s^{NS}+k_n)}{2}-\frac{p_n^{NS}}{(k_s^{NS}-k_n)}$	-	$\frac{2p_n^{NS}-(k_s^{NS}-k_n)^2}{2(k_s^{NS}-k_n)}$
Model NR	$\frac{(1-k_r)+(1-k_n)}{2}-\frac{(p_n^{NR}-p_r^{NR})}{(k_r-k_n)}$	$\frac{(p_n^{NR}-p_r^{NR})}{(k_r-k_n)}-\frac{(k_r-k_n)}{2}-\sqrt{2p_r^{NR}}$	-
Model NRS	$\frac{(1-k_r)+(1-k_n)}{2}-\frac{(p_n^{NRS}-p_r^{NRS})}{(k_r-k_n)}$	$\frac{(p_n^{NRS}-p_r^{NRS})}{(k_r-k_n)}-\frac{(k_s^{NRS}-k_n)}{2}-\frac{p_r^{NRS}}{(k_s^{NRS}-k_r)}$	$\frac{2p_r^{NRS}-(k_s^{NRS}-k_r)^2}{2(k_s^{NRS}-k_r)}$

Table EC.2 Product Demand

EC.4. Numerical Analysis

Although we can obtain the analytical solutions under each model, we perform a comprehensive numerical study for some of the analyses and expression comparisons. For the baseline scenario, we set $c_n = 0.1$. The literature suggests a wide range of operating cost ratios as compared to manufacturing costs. For example, the operating cost of heavy equipment can range from 50% (Gransberg and Rueda 2020) to more than 200% of its manufacturing cost (Matsumoto 2019). We set $k_n \in [\frac{1}{3}c_n, 3c_n]$ to explore a wide range of operating cost ratios. A typical remanufactured product can save 40% to 65% of the original manufacturing cost (Giutini and Gaudette 2003). Thus, we let $c_r \in [0.1c_n, 0.9c_n]$, and $c_s \in [0.1c_n, 0.9c_n]$ to include the practical parametric space. We set $k_r \in [k_n, 2k_n]$ to allow the operating cost of the remanufactured product to vary from a competitive level to 100% higher than that of the new product. The pooling level is set to be $\gamma \in [0.1, 1]$. We set the baseline values for environmental impact parameters – $\delta_n = 0.1$, $\eta_n = 0.1$, and $\eta_r = 0.12$ – to investigate the implications of varying the manufacturing impact of the remanufactured product ($\delta_r \in [0, \delta_n]$) on the environmental performance of jointly adopting servicizing and remanufacturing. When presenting numerical results, we select different stepsizes and values to best represent the properties stated in the propositions. Thus, although model calibration is not pursued due to the lack of proprietary data, the test bed we select for the numerical study covers a wide range of possible parameter values.

EC.5. Technical Results and Proofs

EC.5.1. Proof of Demand Functions and Optimal Prices

Utility U_i is strictly concave in τ_i $(i \in \{n, r, s\})$. Thus, the utility maximizing τ_i^* is such that $d(U_i)/d\tau_i = 0$. Therefore, the optimal usage level is $\tau_i^* = \theta - bk_i, i \in \{n, r, s\}$. Then we have the optimum utilities as follows: $U_n^* = \frac{(\theta-bk_n)^2}{2b} - p_n, U_r^* = \frac{(\theta-bk_r)^2}{2b} - p_r, U_s^* = \frac{(\theta-bk_s)^2}{2b}$. Thus, $U_n^* - U_r^* = \frac{(k_r-k_n)(2\theta-bk_r-bk_n)}{2} - (p_n - p_r)$, $U_r^* - U_s^* = \frac{(k_s-k_r)(2\theta-bk_s-bk_r)}{2} - p_r$; both $U_n^* - U_r^*$ and $U_r^* - U_s^*$ strictly increase in θ, assuming $k_s \geq k_r \geq k_n$. A customer who is indifferent between purchasing a new product and a remanufactured product, i.e., $U_n^* - U_r^* = 0$, has $\theta = \theta_{rn} = \frac{b(k_r+k_n)}{2} + \frac{p_n - p_r}{(k_r-k_n)}$. Similarly, a customer who is indifferent between purchasing a remanufacturing product and a servicized product, i.e., $U_r^* - U_s^* = 0$, has $\theta = \theta_{sr} = \frac{b(k_s+k_r)}{2} + \frac{p_r}{(k_s-k_r)}$. We assume $b = 1$ in the proofs of lemmas and propositions. Let $A = (k_r - k_n)$ and $B = (1 - k_r)$.

Throughout the analysis, we assume a mature market where the quantity of returned cores exceeds the demand for remanufactured products. The parametric condition is obtained by solving for the optimal prices in Model NR and Model NRS and substituting them into the conditions $Q_r^* \leq Q_n^*(+\hat{Q}_s^*)$. The parametric condition is given by:
$\frac{10(c_n-c_s)}{A} \leq \min\left\{ \frac{\{50c_s+[7B-6A-3(Y-2c_n)/\gamma][B+2A+(Y-2c_n)/\gamma]\}^2}{10\gamma[B-3A+(Y+3c_n)/\gamma]^2} - 5(4-2B-A), (5A+6B+2B/A) \right\}$,
where $Y = \sqrt{8[c_n + \gamma(B-A)](3c_n - 3\gamma A - \gamma B) + 9\gamma^2 B^2 - 10c_s\gamma^2}$.

The *min* function on the right-hand side of the inequality corresponds the two conditions under Model NRS and Model NR, respectively. The parametric condition implies that the remanufactured product has relatively low attractiveness because it has either a high remanufacturing (c_s) or operating cost (k_r).

Model N: The new product demand is $Q_n^N = 1 - \theta_n = 1 - k_n - \sqrt{2p_n^N}$. The profit function is $\Pi^N = Q_n^N(p_n^N - c_n)$. To solve for $p_n^{N^*}$, we let $\frac{d\Pi^N}{dp_n^N} = \frac{c_n - 3p_n^N}{\sqrt{2p_n^N}} + 1 - k_n = 0$ and obtain $p_n^{N^*} = \frac{(1-k_n)^2+3c_n+(1-k_n)\sqrt{(1-k_n)^2+6c_n}}{9}$.

Model NS: The new product demand is $Q_n^{NS} = 1 - \frac{(k_s^{NS}+k_n)}{2} - \frac{p_n^{NS}}{(k_s^{NS}-k_n)}$, and the servicized product demand is $Q_s^{NS} = \frac{2p_n^{NS}-(k_s^{NS}-k_n)^2}{2(k_s^{NS}-k_n)}$. Further, the number of servicized products is $\hat{Q}_s^{NS} = \Omega_s^{NS}/\gamma = \int_{\theta_s}^{\theta_{sn}} \tau_s^* d\theta = \frac{[(k_s^{NS}-k_n)^2-2p_n^{NS}]^2}{8\gamma(k_s^{NS}-k_n)^2}$. The profit function is $\Pi^{NS} = Q_n^{NS}(p_n^{NS} - c_n) + \Omega_s^{NS}(k_s^{NS} - k_n) - \hat{Q}_s^{NS}c_n$. We let

$$\frac{\partial \Pi^{NS}}{\partial p_n^{NS}} = 1 - k_s^{NS} - \frac{c_n}{2\gamma} - \frac{p_n^{NS} - c_n}{k_s^{NS} - k_n} - \frac{p_n^{NS} c_n}{(k_s^{NS} - k_n)^2 \gamma},$$
$$\frac{\partial \Pi^{NS}}{\partial k_s^{NS}} = \frac{[2p_n^{NS} - (k_s^{NS} - k_n)^2]\{\gamma(k_s^{NS} - k_n)[]2p_n^{NS} - 4c_n - 3(k_s^{NS} - k_n)^2] + 2c_n[(k_s^{NS} - k_n)^2 + 2p_n^{NS}]\}}{8\gamma(k_s^{NS} - k_n)^3}.$$

By setting $\frac{\partial \Pi^{NS}}{\partial p_n^{NS}} = 0$, we have $p_n^{NS} = \frac{(k_s^{NS}-k_r)[2(k_s^{NS}-k_n)(1-k_s^{NS})\gamma + c_n(k_s^{NS}-k_n+2\gamma)]}{2[c_n+\gamma(k_s^{NS}-k_n)]}$. By substituting the expression above into $\frac{\partial \Pi^{NS}}{\partial k_s^{NS}} = 0$ and solving for k_s^{NS}, we have

$$k_s^{NS1} = \frac{1 + 2k_n - \sqrt{(1-k_n)^2 + 6c_n}}{3}, k_s^{NS2} = \frac{1 + 2k_n + \sqrt{(1-k_n)^2 + 6c_n}}{3},$$
$$k_s^{NS3} = \frac{4k_n\gamma + \gamma - 2c_n - X}{5\gamma}, k_s^{NS4} = \frac{4k_n\gamma + \gamma - 2c_n + X}{5\gamma},$$

where $X = \sqrt{24c_n^2 + (1-k_n)^2\gamma^2 - 2c_n\gamma[5\gamma - 8(1-k_n)]}$. We can obtain the corresponding solutions for p_n^{NS} by substituting k_s^{NSi} $(i \in \{1,2,3,4\})$ into the expressions of p_n^{NS} derived earlier. Now we have four sets of solutions as critical points of the objective function. It is easy to show that for the first two sets of solutions (i.e. $\{p_n^{NS1}, k_s^{NS1}\}$ and $\{p_n^{NS2}, k_s^{NS2}\}$), we always have $Q_s^{NS} = 0$. Further, for

$i \in \{3,4\}$, we have $\Pi^{NS3} - \Pi^{NS4} = -\frac{2\sqrt{\{24c_n^2+(1-k_n)^2\gamma^2-2c_n\gamma[5\gamma-8(1-k_n)]\}^3}}{25\gamma^2} < 0$. That is, $\Pi^{NS4} \geq \Pi^{NS3}$. Therefore, $\{p_n^{NS4}, k_s^{NS4}\}$ is the optimal solution. The expressions are not provided for brevity.

Model NR: The new product demand is $Q_n^{NR} = 1 - \theta_{rn} = \frac{(1-k_n)^2-(1-k_r)^2-2(p_n^{NR}-p_r^{NR})}{2(k_r-k_n)}$, and the remanufactured product demand is $Q_r^{NR} = \theta_{rn} - \theta_r = \frac{(p_n^{NR}-p_r^{NR})}{(k_r-k_n)} - \frac{(k_r-k_n)}{2} - \sqrt{2p_r^{NR}}$. The profit function is $\Pi^{NR} = Q_n^{NR}(p_n^{NR} - c_n) + Q_r^{NR}(p_r^{NR} - c_r)$. To solve for the interior solution $\{p_n^{NR*}, p_r^{NR*}\}$, we let $\frac{\partial \Pi^{NR}}{\partial p_n}^{NR} = \frac{2(c_n-c_r)+(1-k_n)^2-(1-k_r)^2-4(p_n^{NR}-p_r^{NR})}{2(k_r-k_n)} = 0$, and $\frac{\partial \Pi^{NR}}{\partial p_r^{NR}} = \frac{2(p_n^{NR}-p_r^{NR})-(c_n-c_r)}{k_r-k_n} - \frac{k_r-k_n}{2} - \sqrt{\frac{p_r}{2}}(3 - \frac{c_r}{p_r}) = 0$. We have $p_n^{NR*} = \frac{P}{9} + \frac{[A(A+2B)+2(c_n-c_r)]}{4}$, and $p_r^{NR*} = \frac{P}{9}$, where $P = 3c_r + B^2 + B\sqrt{6c_r + B^2}$. Since $\frac{10(c_n-c_s)}{A} \leq (5A + 6B + 2B/A)$, using standard algebra, we can show we always have $Q_r^{NR*} \leq Q_n^{NR*}$.

Model NRS: The new product demand is $Q_n^{NRS} = \frac{(1-k_r)+(1-k_n)}{2} - \frac{(p_n^{NRS}-p_r^{NRS})}{(k_r-k_n)}$, the remanufactured product demand is $Q_r^{NRS} = \frac{(p_n^{NRS}-p_r^{NRS})}{(k_r-k_n)} - \frac{(k_s^{NRS}-k_n)}{2} - \frac{p_r^{NRS}}{(k_s^{NRS}-k_r)}$, and the servicized product demand is $Q_s^{NRS} = \frac{2p_r^{NRS}-(k_s^{NRS}-k_r)^2}{2(k_s^{NRS}-k_r)}$. Further, the number of servicized products is $\hat{Q}_s^{NRS} = \Omega_s^{NRS}/\gamma = \int_{\theta_s}^{\theta_{sr}} \tau_s^* d\theta = \frac{[(k_s^{NRS}-k_r)^2-2p_r^{NRS}]^2}{8\gamma(k_s^{NRS}-k_r)^2}$. The profit function is $\Pi^{NRS} = Q_n^{NRS}(p_n^{NRS} - c_n) + [\Omega_s^{NRS}(k_s^{NRS} - k_n) - \hat{Q}_s^{NRS} c_n] + Q_r(p_r^{NRS} - c_s)$. We let

$$
\begin{aligned}
\frac{\partial \Pi^{NRS}}{\partial p_n^{NRS}} &= \frac{2(c_n - c_s) + (1-k_n)^2 - (1-k_r)^2 - 4(p_n^{NRS} - p_r^{NRS})}{2(k_r - k_n)}, \\
\frac{\partial \Pi^{NRS}}{\partial p_r^{NRS}} &= \frac{c_n}{2\gamma} + \frac{2p_n^{NRS} - c_n}{k_r - k_n} + \frac{2p_r^{NRS}(\gamma - c_n)}{(k_s^{NRS} - k_n)^2} + \frac{(c_s - 2p_r^{NRS})(k_s^{NRS} - k_n)}{(k_r - k_n)(k_s^{NRS} - k_r)} - (k_s^{NRS} - k_n), \\
\frac{\partial \Pi^{NRS}}{\partial k_s^{NRS}} &= -\frac{2c_n[(k_s^{NRS} - k_r)^2 - 2p_r^{NRS}][(k_s^{NRS} - k_r)^2 + 2p_r^{NRS}]}{8\gamma(k_s^{NRS} - k_r)^3} + \\
&\quad \frac{\gamma[(k_s^{NRS} - k_r)^2 - 2p_r^{NRS}][(k_r + 2k_n - 3k_s^{NRS})(k_s^{NRS} - k_r)^2 + 2p_r^{NRS}(k_s^{NRS} + 2k_n - 3k_r) - 4c_s(k_s^{NRS} - k_r)]}{8\gamma(k_s^{NRS} - k_r)^3}.
\end{aligned}
$$

By setting $\frac{\partial \Pi^{NRS}}{\partial p_n^{NRS}} = 0$, we have $p_n^{NRS} = \frac{2(c_n-c_s)+(1-k_n)^2-(1-k_r)^2+4p_r^{NRS}}{4}$. By setting $\frac{\partial \Pi^{NRS}}{\partial p_r^{NRS}} = 0$ and substitute p_n^{NRS} with the expression derived above, we can obtain an expression of p_r^{NRS} with respect to k_s^{NRS} as $p_r^{NRS} = \frac{(k_s^{NRS}-k_r)\{2c_s\gamma+(k_s^{NRS}-k_r)[2\gamma(1-k_s^{NRS})-\gamma(k_r-k_n)+c_n]\}}{2[\gamma(k_s^{NRS}-k_r)-\gamma(k_r-k_n)+c_n]}$. By substituting the two expressions above into $\frac{\partial \Pi^{NRS}}{\partial k_s^{NRS}}$ and setting $\frac{\partial \Pi^{NRS}}{\partial k_s^{NRS}} = 0$, we solve for k_s^{NRS}. The four roots we obtained for k_s^{NRS} are:

$$
\begin{aligned}
k_s^{NRS1} &= \frac{1 + 2k_r - \sqrt{B^2 + 6c_s}}{3}, k_s^{NS2} = \frac{1 + 2k_r + \sqrt{B^2 + 6c_s}}{3}, \\
k_s^{NRS3} &= \frac{-(2c_n - 2\gamma A + 4\gamma B - 5\gamma) - Y}{5\gamma}, \\
k_s^{NRS4} &= \frac{-(2c_n - 2\gamma A + 4\gamma B - 5\gamma) + Y}{5\gamma},
\end{aligned}
$$

where $Y = \sqrt{8[c_n + \gamma(B - A)](3c_n - 3\gamma A - \gamma B) + 9\gamma^2 B^2 - 10c_s\gamma^2}$. We can obtain the corresponding solutions for p_n^{NRS} and p_r^{NRS} by substituting k_s^{NRSt} ($t \in \{1,2,3,4\}$) into the expressions of p_n^{NRS} and p_r^{NRS} derived earlier. Now we have four sets of solutions as critical points of the objective function. It is easy to show that the first two sets of solutions (i.e. $\{p_n^{NRS1}, p_n^{NRS1}, k_s^{NRS1}\}$ and $\{p_n^{NRS2}, p_n^{NRS2}, k_s^{NRS2}\}$, we always have $Q_s^{NRSt} = \theta_{sr}^{(t)} - \theta_s^{(t)} = 0$. Further, for $t \in \{3,4\}$, we have

$\Pi^{NRS3} - \Pi^{NRS4} = -\frac{2\sqrt{[8(c_n+\gamma B-\gamma A)(3c_n-3\gamma A-\gamma B)+9\gamma^2 B^2-10c_s\gamma^2]^3}}{25\gamma^2} < 0$. That is, $\Pi^{NRS4} \geq \Pi^{NRS3}$. Therefore, $\{p_n^{NRS4}, p_n^{NRS4}, k_s^{NRS4}\}$ is the optimal solution. The expressions are not provided for brevity. Since $\frac{10(c_n-c_s)}{A} \leq \frac{\{50c_s+[7B-6A-3(Y-2c_n)/\gamma][B+2A+(Y-2c_n)/\gamma]\}^2}{10\gamma[B-3A+(Y+3c_n)/\gamma]^2} - 5(4-2B-A)$, using standard algebra, we can show that we always have $Q_r^{NRS*} \leq (Q_n^{NRS*} + \Omega_s^{NRS*}/\gamma)$. $\square$

EC.5.2. Proof of Proposition 1

Building upon existing knowledge that high pooling makes servicizing a favorable strategy (Agrawal and Bellos 2017), we first find the pooling threshold beyond which the firm adopts servicizing and use it as a measure to assess the attractiveness of servicizing. Using optimal prices derived in §EC.5.1, we know $Q_s^{NS*} = \frac{6[3c_n+\gamma(1-k_n)]-4X}{5\gamma}$, and $Q_s^{NRS*} = \frac{6(3c_n-3\gamma A+\gamma B)-4Y}{5\gamma}$. Therefore, the sufficient condition for $Q_s^{NS*} \geq 0$ is $\gamma \geq \frac{3c_n}{2(6c_n+(1-k_n)^2)^{1/2}-(1-k_n)}$, and the sufficient condition for $Q_s^{NRS*} \geq 0$ is $\gamma \geq \frac{3c_n}{2(6c_s+B^2)^{1/2}+(3A-B)}$.

Let $\Gamma^N(k_n, c_n) = \frac{3c_n}{2(6c_n+(1-k_n)^2)^{1/2}-(1-k_n)}$ denote the threshold beyond which servicizing is adopted without remanufacturing. Then when $\gamma \geq \Gamma^N$, $Q_s^{NS*} \geq 0$, and thus we have $\Pi^{NS*} \geq \Pi^{N*}$.

Let $\Gamma^{NR}(k_r, k_n, c_n, c_s) = \frac{3c_n}{2(6c_s+B^2)^{1/2}+(3A-B)}$ denote the threshold beyond which servicizing is adopted with remanufacturing. Then when $\gamma \geq \Gamma^{NR}(k_r, k_n, c_n, c_s)$, $Q_s^{NRS*} \geq 0$. Under this condition, when $c_s \leq c_r$, we always have $\Pi^{NRS*} \geq \Pi^{NR*}$. When $c_s > c_r$, the sufficient condition for $\Pi^{NRS*} \geq \Pi^{NR*}$ becomes $\gamma \geq \Gamma^{NR}(k_r, k_n, c_n, c_r, c_s)$. Note that $\Gamma^{NR}(k_r, k_n, c_n, c_r, c_s) > \Gamma^{NR}(k_r, k_n, c_n, c_s)$.

For $Q_r^{NRS*} \geq 0$, a necessary condition for Model NRS, to hold, we need $c_s \leq C_s(k_r, k_n, c_n, \gamma) = \frac{\gamma\left(-13k_n^2+8k_nk_r+18k_n+5k_r^2-18k_r\right)-2c_n(32k_r-32k_n-5\gamma)+12X(k_r-k_n)}{10\gamma}$. This condition is required for a meaningful comparison between Γ^{NR} and Γ^N. Under this condition, $\Gamma^N(k_n, c_n) \leq \Gamma^{NR}(k_r, k_n, c_n, c_s) \leq \Gamma^{NR}(k_r, k_n, c_n, c_r, c_s)$ is always true.

We next compare the market size between Model NS and Model NRS. Let M^j be the total market size under Model j, $j \in \{N, NS, NR, NRS\}$. From the quantities derived in §EC.5.1, it is immediate that the market size of Model NS – $M^{NS} = 1 - k_s^{NS*}$, and the market size of Model NRS – $M^{NRS} = 1 - k_s^{NRS*}$. Then when $c_s \leq C_s(k_r, k_n, c_n, \gamma)$, we always have $k_s^{NRS*} \geq k_s^{NS*}$. That is, $M^{NRS} \leq M^{NS}$. $\square$

EC.5.3. Proof of Proposition 2

In the proof of Proposition 1, we know that $C_s(k_r, k_n, c_n, \gamma)$ is the threshold below which remanufacturing becomes attractive in the presence of servicizing. Further, the condition for remanufacturing to be attractive without servicizing is given by $Q_r^{NR*} > 0$, or $c_r \leq C_r(k_r, k_n, c_n) = \frac{1}{6}\left(-4(k_r-k_n)\sqrt{6c_n+7k_n^2-2k_n(6k_r+1)+6k_r^2+1}+6c_n+11k_n^2-20k_nk_r-2k_n+9k_r^2+2k_r\right)$. In other words, when $c_s \leq C_s(k_r, k_n, c_n, \gamma)$ and $c_r \geq C_r(k_r, k_n, c_n)$, remanufacturing is not attractive without servicizing and becomes attractive with servicizing. The opposite is true when $c_s > C_s(k_r, k_n, c_n, \gamma)$ and $c_r < C_r(k_r, k_n, c_n)$. This completes the proof. $\square$

EC.5.4. Proof of Proposition 3

When $c_s \le c_r$ and both Model NR and Model NS exists, recall from EC.5.2 that the sufficient condition for $\Pi^{NRS*} > \Pi^{NR*}$ is $\gamma > \Gamma^{NR}(k_r, k_n, c_n, c_s)$. This is equivalent to $c_s > C_{s2}(k_r, k_n, c_n, \gamma)$, where $C_{s2}(k_r, k_n, c_n, \gamma) = \frac{(3c_n+\gamma+3k_n\gamma-4k_r\gamma)^2}{24\gamma^2} - \frac{(1-k_r)^2}{6}$. Further, recall from EC.5.3 that when $c_s < C_s(k_r, k_n, c_n, \gamma)$, $Q_r^{NRS*} > 0$, and thus $\Pi^{NRS*} > \Pi^{NS*}$. Therefore, the joint adoption is preferred when $C_{s2}(k_r, k_n, c_n, \gamma) < c_s < C_s(k_r, k_n, c_n, \gamma)$.

When $c_s > c_r$, the conditions derived above ensure $Q_s^{NRS*} > 0$ and $Q_r^{NRS*} > 0$ but are not sufficient for $\Pi^{NRS*} > \Pi^{NR*}$. Let $\Pi^{NRS*} > \Pi^{NR*}$ and rearrange terms, we obtain $675c_r^2 + c_rQ + 100(k_r - k_n)[6c_r + (1 - k_r)^2]^{3/2} < 675c_s^2 - L - c_sP + \frac{1080c_s(k_r-k_n\sqrt{K-10c_s\gamma^2})}{\gamma} - M\sqrt{K - 10c_s\gamma^4}$. Here, $K = 8[c_n + \gamma(B - A)](3c_n - 3\gamma A - \gamma B) + 9\gamma^2B^2$, $L = \frac{8(k_r-k_n)(\gamma+3c_n+3\gamma k_n-4\gamma k_r)\left(531c_n^2+354\gamma c_n(3k_n-4k_r+1)+\gamma^2\left(531k_n^2+354k_n(1-4k_r)+4k_r(221k_r-88)-1\right)\right)}{\gamma^3}$, $M = \frac{108(k_n-k_r)\left(24c_n^2+16\gamma c_n(3k_n-4k_r+1)+\gamma^2\left(-64k_nk_r+8k_n(3k_n+2)+41k_r^2-18k_r+1\right)\right)}{\gamma^4}$, $P = \frac{135(8A(k_r-k_n)+\gamma(10\gamma c_n+64c_n(k_n-k_r)+\gamma(59k_n-77k_r+18)(k_n-k_r)))}{\gamma^2}$, $Q=75(k_r - k_n)(9(k_r - k_n) - 6(1 - k_r)) - 1350c_n$. Let $F_r(k_r, k_n, c_n, c_r) = 675c_r^2 + c_rQ + 100(k_r - k_n)[6c_r + (1 - k_r)^2]^{3/2}$ and $F_s(k_r, k_n, c_n, c_s, \gamma) = 675c_s^2 - L - c_sP + \frac{1080c_s(k_r-k_n\sqrt{K-10c_s\gamma^2})}{\gamma} - M\sqrt{K - 10c_s\gamma^4}$, then when $C_{s2}(k_r, k_n, c_n, \gamma) < c_s < C_s(k_r, k_n, c_n, \gamma)$ and $F_r(k_r, k_n, c_n, c_r) < F_s(k_r, k_n, c_n, c_s, \gamma)$, we have $\Pi^{NRS*} > \Pi^{NR*}$ and $\Pi^{NRS*} > \Pi^{NS*}$.

We have $\frac{\partial C_s(k_r,k_n,c_n,\gamma)}{\partial\gamma} = \frac{16c_n(k_r-k_n)\left(-3\gamma+2\sqrt{24c_n^2-2\gamma c_n(5\gamma+8k_n-8)+\gamma^2(1-k_n)^2}-9c_n+3\gamma k_n\right)}{5\gamma^2\sqrt{24c_n^2-2\gamma c_n(5\gamma+8k_n-8)+\gamma^2(1-k_n)^2}}$, which is negative under the condition $Q_s^{NS*} > 0$. That is, $C_s(k_r, k_n, c_n, \gamma)$ decreases in γ. Further, $\frac{\partial C_{s2}}{\partial\gamma} = -\frac{c_n(\gamma+3c_n+3\gamma k_n-4\gamma k_r)}{4\gamma^3}$. Given $Q_s^{NRS*} > 0$, $\frac{\partial C_{s2}}{\partial\gamma} < 0$. That is, $C_{s2}(k_r, k_n, c_n, \gamma)$ decreases in γ.

Finally, we have $\frac{\partial(C_s-C_{s2})}{\partial k_r} = \frac{3\left(-3\gamma+2\sqrt{24c_n^2-2\gamma c_n(5\gamma+8k_n-8)+\gamma^2(k_n-1)^2}-9c_n+3\gamma k_n\right)}{5\gamma}$. Given $Q_s^{NS*} > 0$, $\frac{\partial(C_s-C_{s2})}{\partial k_r} < 0$. That is, $(C_s - C_{s2})$ decreases in k_r. This completes the proof. □

EC.5.5. Proof of Proposition 4

When both Model NR and Model NRS exist, let $\Delta Q_r = Q_r^{NRS*} - Q_r^{NR*}$. Then we have $\frac{\partial\Delta Q_r}{c_s} = -\frac{1}{2(k_r-k_n)} - \frac{3\gamma}{Y} < 0$, and $\frac{\partial^2\Delta Q_r}{c_s^2} = -\frac{15\gamma^3}{Y^3} < 0$. Therefore, ΔQ_r concave decreases in c_s. Thus, there exists a threshold $C_{s3} = \frac{2}{15}\left(\frac{3\sqrt{3}(k_r-k_n)D}{\gamma} - 6k_n^2 + k_n(-4k_r - 5Z + 16) + 10k_r^2 + 5k_rZ - 16k_r\right) - \frac{32c_n(k_r-k_n)}{5\gamma} + c_r$, where $D = \sqrt{-\left(-72c_n^2 + 48\gamma c_n(k_n - 1) + \gamma^2\left(30c_r + 12k_n^2 - 40k_nk_r - 20k_nZ + 16k_n + 25k_r^2 + 20k_rZ - 10k_r - 3\right)\right)}$ and $Z = \sqrt{6c_s + (1 - k_r)^2}$, such that when $c_s \le C_{s3}(k_r, k_n, c_n, \gamma)$, $(Q_r^{NRS*} - Q_r^{NR*}) \ge 0$.

Further, we have $\frac{\partial C_{s3}}{\partial\gamma} = -\frac{16c_n(k_r-k_n)\left(9\sqrt{3}c_n-2D+3\sqrt{3}\gamma(1-k_n)\right)}{5\gamma^2D}$, which can be shown negative under the condition $Q_s^{NRS*} \ge 0$.

Let $\Delta E_1 = E^{NRS*} - E^{NR*}$, and $\Delta E_2 = E^{NRS*} - E^{NS*}$. Then $\frac{\partial\Delta E_1}{\delta_r} = Q_r^{NRS*} - Q_r^{NR*}$, and $\frac{\partial^2\Delta E_1}{\delta_r^2} = 0$. From above, we know that when $c_s \le C_{s3}(k_r, k_n, c_n, \gamma)$, $\frac{\partial\Delta E_1}{\delta_r} = (Q_r^{NRS*} - Q_r^{NR*}) \ge 0$. Thus, there exists a threshold Δ_1 such that when $\delta_r < \Delta_1$, we have $E^{NRS*} < E^{NR*}$. Similarly, because

$\frac{\partial \Delta E_2}{\delta_r} = Q_r^{NRS*} > 0$, there exists a threshold Δ_2 such that when $\delta_r < \Delta_2$, we have $E^{NRS*} < E^{NS*}$. Let $\Delta = MIN(\Delta_1, \Delta_2)$. Then when $\delta_r < \Delta$, we have $E^{NRS*} < E^{NR*}$ and $E^{NRS*} < E^{NS*}$.

When $c_s \geq C_{s3}(k_r, k_n, c_n, \gamma)$, $\frac{\partial \Delta E_1}{\delta_r} = (Q_r^{NRS*} - Q_r^{NR*}) \leq 0$. Thus, there exists a threshold Δ_1 such that when $\delta_r > \Delta_1$, we have $E^{NRS*} < E^{NR*}$. Combining the results comparing E^{NRS*} and E^{NS*} above, we know that when $\Delta_1 < \delta_r < \Delta_2$, we have $E^{NRS*} < E^{NR*}$ and $E^{NRS*} < E^{NS*}$. This completes the proof. □

EC.6. Win-Win Conditions of the Joint Adoption

Combining the insights derived in Proposition 4 and the observations from Figure 4, in Figure EC.1 below, we provide a simplified view of the win-win region against two dimensions: the remanufacturing cost with servicizing and the environmental impact ratio ($\frac{\delta_r+\eta_r}{\delta_n+\eta_n}$). Observe the win-win region exists (1) when both the remanufacturing cost with servicizing and the environmental impact ratio are high or low if adopting servicizing in the presence of remanufacturing (Figure EC.1a), and (2) when the environmental impact ratio is low if adopting remanufacturing in the presence of servicizing (Figure EC.1b). Moreover, as discussed in §5.2, an increase in pooling expands the win-win region when adopting servicizing in the presence of remanufacturing but shrinks the same region when adopting remanufacturing in the presence of servicizing.

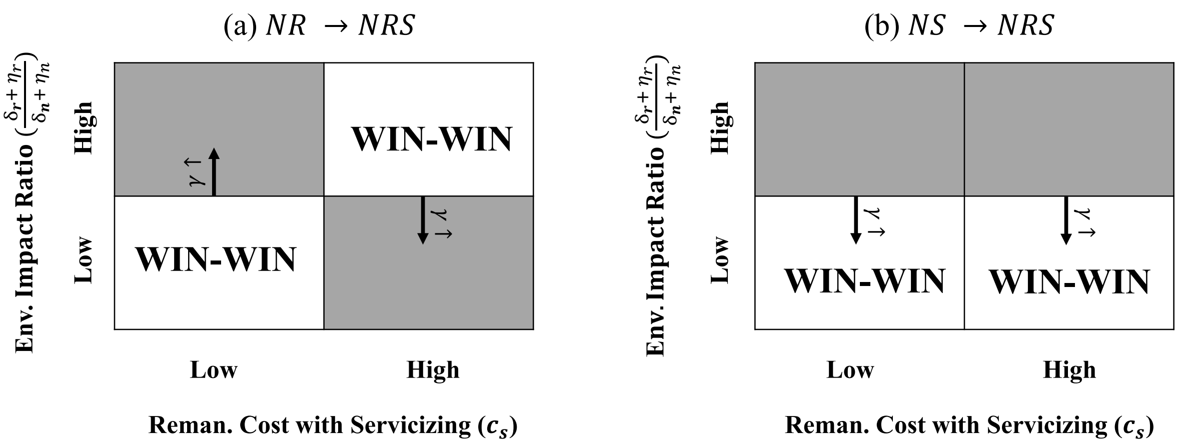

Figure EC.1 **Win-Win Region of the Joint Adoption of Servicizing and Remanufacturing**

EC.7. Analysis of Ownership-Dependent Operating Cost

In our analysis thus far, we assumed that the operating cost of a new product (sold or servicized) is k_n irrespective of the ownership (customers or firm). However, in practice, this may not always be the case. Consider products maintained by a firm under servicizing. On the one hand, the firm maintains a pool of products that allow it to enjoy economies of scale, driving the corresponding operating cost down. On the other hand, careless use of the products in customers' hands due to the lack of ownership may lead to a higher operating cost. Thus, the resulting operating cost of a servicized product can be higher or lower than that of a customer-owned product, i.e., k_n. To capture this, we let the operating cost of a servicized product be $k_n^{'}$. As customers' operating costs remain the same, the expressions of product quantities are the same as those in Table EC.2. The profit function of Model NS becomes: $\Pi^{NS^{'}} = Q_n^{NS}(p_n^{NS} - c_n) + \Omega_s^{NS}(k_s^{NS} - k_n^{'}) - \hat{Q}_s^{NS} c_n$, and the profit function of Model NRS becomes $\Pi^{NRS^{'}} = Q_n^{NRS}(p_n^{NRS} - c_n) + [\Omega_s^{NRS}(k_s^{NRS} - k_n^{'}) - \hat{Q}_s^{NRS} c_n] + Q_r(p_r^{NRS} - c_s)$.

Using the same procedure specified in §EC.5.1, we obtain the optimal prices for both models as: $\{p_n^{NS*} = -\frac{(k_n - k_s^{NS*})(c_n(2\gamma - k_n + k_s^{NS*}) + \gamma(k_n - k_s^{NS*})(k_n - k_n^{'} + 2k_s^{NS*} - 2))}{2(c_n + \gamma(-2k_n + k_n^{'} + k_s^{NS*}))}, k_s^{NS*} = \frac{6k_n\gamma - 2k_n^{'} + \gamma - 2c_n + X^{'}}{5\gamma}\}$, and $\{p_n^{NRS*} = \frac{1}{4}\{-\frac{2(k_r - k_s^{NRS*})(2\gamma c_s - (k_r - k_s^{NRS*})(c_n + \gamma(k_n^{'} - k_r - 2k_s^{NRS*} + 2)))}{c_n + \gamma(k_n^{'} - 2k_r + k_s^{NRS*})} + 2c_n - 2c_s + k_n^2 - 2k_n - k_r^2 + 2k_r\}$, $p_r^{NRS*} = -\frac{(k_r - k_s^{NRS*})(c_n(k_s^{NRS*} - k_r) + 2\gamma c_s + \gamma(k_r - k_s^{NRS*})(-k_n^{'} + k_r + 2k_s^{NRS*} - 2))}{2(c_n + \gamma(k_n^{'} - 2k_r + k_s^{NRS*}))}$, $k_s^{NRS*} = \frac{6k_r\gamma - 2k_n^{'} + \gamma - 2c_n + Y^{'}}{5\gamma}\}$, where $X^{'} = \sqrt{24c_n^2 - 2\gamma c_n(5\gamma + 32k_n - 24k_n^{'} - 8) + \gamma^2[41k_n^2 - 2k_n(32k_n^{'} + 9) + 24{k_n^{'}}^2 + 16k_n^{'} + 1]}$, and $Y^{'} = \sqrt{24c_n^2 + 16\gamma c_n(3k_n^{'} - 4k_r + 1) + \gamma^2(-10c_s + 24{k_n^{'}}^2 - 64k_n^{'}k_r + 16k_n^{'} + 41k_r^2 - 18k_r + 1)}$.

We next discuss the implications of having different operating costs on the main results. As some of the comparisons are analytically intractable, we resort to a numerical analysis for the comparisons. First, by checking the conditions for $Q_s^{NS*} \geq 0$ and $Q_s^{NRS*} \geq 0$, we obtain $\Gamma^N = \frac{3c_n}{2(6c_n + (1-k_n)^2)^{1/2} + 4k_n - 3k_n^{'} - 1}$ and $\Gamma^{NR} = \frac{3c_n}{2(6c_s + (1-k_r)^2)^{1/2} + 4k_r - 3k_n^{'} - 1}$. We numerically verified that when $Q_r^{NRS*} \geq 0$, we always have $\Gamma^{NR} \geq \Gamma^N$. Further, we obtain the expression of $C_s^{'}(k_r, k_n, k_n^{'}, c_n, \gamma)$. It can be shown that when $k_n^{'} > k_n$, $C_s^{'}(k_r, k_n, k_n^{'}, c_n, \gamma) > C_s(k_r, k_n, c_n, \gamma)$. Nevertheless, Proposition 1 continues to hold. Moreover, as the value of $C_r(k_r, k_n, c_n)$ do not change, Proposition 2 still holds.

For Proposition 3, $C_{s2}^{'}(k_r, k_n^{'}, c_n, \gamma) = \frac{(3c_n + \gamma + 3k_n^{'}\gamma - 4k_r\gamma)^2}{24\gamma^2} - \frac{(1-k_r)^2}{6}$. It is evident that $C_{s2}^{'}(k_r, k_n^{'}, c_n, \gamma)$ increases in $k_n^{'}$. Thus, when $c_s < c_r$, Model NRS is preferred if $C_{s2}^{'}(k_r, k_n^{'}, c_n, \gamma) < c_s < C_s^{'}(k_r, k_n, k_n^{'}, c_n, \gamma)$; when $c_s > c_r$, Model NRS is preferred if $C_{s2}^{'}(k_r, k_n^{'}, c_n, \gamma) < c_s < C_s^{'}(k_r, k_n, k_n^{'}, c_n, \gamma)$ and $F_r^{'}(k_r, k_n, k_n^{'}, c_n, c_r) < F_s^{'}(k_r, k_n, k_n^{'}, c_n, c_s, \gamma)$ (expressions for $F_r^{'}$ and $F_s^{'}$ omitted for brevity). This is consistent with Proposition 3 in the main paper.

For Proposition 4, we have $\frac{\partial \Delta Q_r}{c_s} = -\frac{1}{2(k_r - k_n)} - \frac{3\gamma}{Y^{'}} < 0$, and $\frac{\partial^2 \Delta Q_r}{c_s^2} = -\frac{15\gamma^3}{{Y^{'}}^3} < 0$. Therefore, there exists a threshold $C_{s3}^{'} = c_r + \frac{2(k_r - k_n)[-48c_n + 3\sqrt{3}D^{'} + \gamma(54k_n - 48k_n^{'} + 10k_r + 5Z - 16)]}{15\gamma}$ (the expression of $D^{'}$ not provided for brevity), such that when $c_s \leq C_{s3}^{'}(k_r, k_n, k_n^{'}, c_n, \gamma)$, $(Q_r^{NRS*} - Q_r^{NR*}) \geq 0$. Through numerical analysis, we observe that $C_{s3}^{'}(k_r, k_n, k_n^{'}, c_n, \gamma)$ increases in $k_n^{'}$. Nevertheless, Proposition 4 continues to hold.

To summarize, we find that when the firm is more cost-efficient in maintaining and operating its products, the decreased operating cost makes servicized products more attractive and reduces the demand for remanufactured products (i.e., a lower value of $C_s(k_r, k_n, c_n, \gamma)$ in Proposition 2).

A lower $k_n^{'}$ can have a positive or negative impact on the environment. If remanufactured products have a high use impact, a decrease in the remanufactured product demand can lower the total environmental impact. Contrarily, if a remanufactured product emits a similar level of greenhouse gas in the use phase as a new product and saves considerable energy in the manufacturing phase, replacing remanufactured products with servicized ones due to a lower $k_n^{'}$ can harm the environment.

EC.8. Analysis of Differentiated Valuation for Remanufactured Products

In practice, customers may value remanufactured products differently. For example, some customers may discount the valuation of remanufactured products due to perceived quality risk (Abbey et al. 2017, Guide and Li 2010). In contrast, with a global trend to slow down climate change, customers who appraise the environmental benefit of energy and virgin material savings may place an additional value on remanufactured products (Atasu et al. 2008). This extension explores the model's robustness with customer segments in the market that have differentiated valuations for remanufactured products.

Let the fraction of green customers in the market be $\alpha \in [0,1]$. The green customers derive an extra utility g_r from a remanufactured product over a new (servicized) product. Let the fraction of regular customers be $(1-\alpha)$; these customers discount the utility of using a remanufactured product by d_r. Thus, for a remanufactured product, a green customer derives a utility $U_r^g = \left\{\frac{1}{b}(\theta\tau_r - \frac{\tau_r^2}{2}) - p_r - k_r\tau_r + g_r\right\}$, and a regular customer derives a utility $U_r^d = \left\{\frac{1}{b}(\theta\tau_r - \frac{\tau_r^2}{2}) - p_r - k_r\tau_r - d_r\right\}$.

The result below states the demand for each product under this scenario. Note that the presence of the two customer segments only affects the demand under Model NR and Model NRS.

PROPOSITION EC.1. *The product demand q_i^j ($i \in \{n,r,s\}$, $j \in \{NR, NRS\}$) in the presence of customers with differentiated valuations are as follows.*

Model NR: $q_n^{NR} = Q_n^{NR} - \frac{[\alpha g_r - (1-\alpha)d_r]}{(k_r-k_n)}$, $q_r^{NR} = Q_r^{NR} + \frac{[\alpha g_r - (1-\alpha)d_r]}{(k_r-k_n)} + \sqrt{2p_r} - [\alpha\sqrt{2(p_r-g_r)} + (1-\alpha)\sqrt{2(p_r+d_r)}]$.

Model NRS: $q_n^{NRS} = Q_n^{NRS} - \frac{[\alpha g_r - (1-\alpha)d_r]}{(k_r-k_n)}$, $q_r^{NRS} = Q_r^{NRS} + \frac{[\alpha g_r - (1-\alpha)d_r](k_s-k_n)}{(k_s-k_r)(k_r-k_n)}$, $q_s^{NRS} = Q_s^{NRS} - \frac{[\alpha g_r - (1-\alpha)d_r]}{(k_s-k_r)}$.

Proof of Proposition EC.1:

Model NR: using the utility functions, we can derive the indifferent points of usage needs for green customers as: $\theta_{rn}^g = \frac{k_r+k_n}{2} + \frac{p_n-(p_r-g_r)}{(k_r-k_n)}$, $\theta_r^g = k_r + \sqrt{2(p_r-g_r)}$, and the indifferent points for discounting customers as: $\theta_{rn}^d = \frac{k_r+k_n}{2} + \frac{p_n-(p_r+d_r)}{(k_r-k_n)}$, $\theta_r^d = k_r + \sqrt{2(p_r+g_r)}$. Therefore, the demands for each product in the green segment are: $Q_n^{NRg} = (1-\theta_{rn}^g) = \frac{(1-k_n)^2-(1-k_r)^2-2(p_n-p_r+g_r)}{2(k_r-k_n)}$, $Q_r^{NRg} = (\theta_{rn}^g - \theta_r^g) = \frac{(p_n-p_r+g_r)}{(k_r-k_n)} - \frac{(k_r-k_n)}{2} - \sqrt{2(p_r-g_r)}$. The demands for each product in the discounting segment are: $Q_n^{NRd} = (1-\theta_{rn}^d) = \frac{(1-k_n)^2-(1-k_r)^2-2(p_n-p_r-d_r)}{2(k_r-k_n)}$, $Q_r^{NRd} = (\theta_{rn}^d - \theta_r^d) = \frac{(p_n-p_r-d_r)}{(k_r-k_n)} - \frac{(k_r-k_n)}{2} - \sqrt{2(p_r+d_r)}$. The total demand then becomes: $q_n^{NR} = \alpha Q_n^{NRg} + (1-\alpha)Q_n^{NRd}$ and $q_r^{NR} = \alpha Q_r^{NRg} + (1-\alpha)Q_r^{NRd}$. The result follows.

Model NRS: Similar to Model NR, the indifferent points of usage needs for green customers are: $\theta_{rn}^g = \frac{k_r+k_n}{2} + \frac{p_n-(p_r-g_r)}{(k_r-k_n)}$, $\theta_{sr}^g = \frac{k_s+k_r}{2} + \frac{p_r-g_r}{k_s-k_r}$, $\theta_s = k_s$, and the indifferent points for discounting customers are: $\theta_{rn}^d = \frac{k_r+k_n}{2} + \frac{p_n-(p_r+d_r)}{(k_r-k_n)}$, $\theta_{sr}^d = \frac{k_s+k_r}{2} + \frac{p_r+d_r}{k_s-k_r}$, $\theta_s = k_s$. Therefore, the demands for each product in the green segment are: $Q_n^{NRSg} = (1-\theta_{rn}^g) = \frac{(1-k_n)^2-(1-k_r)^2-2(p_n-p_r+g_r)}{2(k_r-k_n)}$, $Q_r^{NRSg} = (\theta_{rn}^g - \theta_{sr}^g) = \frac{p_n-p_r+g_r}{k_r-k_n} - \frac{k_s-k_n}{2} - \frac{p_r-g_r}{k_s-k_r}$, $Q_s^{NRSg} = (\theta_{sr}^g - \theta_s) = \frac{2(p_r-g_r)-(k_s-k_r)^2}{2(k_s-k_r)}$; the demands for each product in the discounting segment are: $Q_n^{NRSd} = (1-\theta_{rn}^d) = \frac{(1-k_n)^2-(1-k_r)^2-2(p_n-p_r-d_r)}{2(k_r-k_n)}$, $Q_r^{NRSd} = (\theta_{rn}^d - \theta_{sr}^d) = \frac{p_n-p_r-d_r}{k_r-k_n} - \frac{k_s-k_n}{2} - \frac{p_r+d_r}{k_s-k_r}$, $Q_s^{NRSd} = (\theta_{sr}^d - \theta_s) = \frac{2(p_r+d_r)-(k_s-k_r)^2}{2(k_s-k_r)}$. The total demand then becomes: $q_n^{NRS} = Q_n^{NRS} + \alpha Q_n^{NRSg} + (1-\alpha)Q_n^{NRSd}$, $q_r^{NRS} = \alpha Q_r^{NRSg} + (1-\alpha)Q_r^{NRSd}$, and $q_s^{NRS} = \alpha Q_s^{NRSg} + (1-\alpha)Q_r^{NRSd}$. The result follows. $\square$

Observe from the result above that under Model NR, when a large pool of green customers attaches a significant extra utility to the remanufactured product (i.e., large α and large g_r), it results in cannibalization of the new product demand and expansion of the remanufactured product market. Under Model NRS, a similar condition leads to the cannibalization of both new product sales and servicizing. The expansion of the remanufacturing market enlarges when customers attach higher extra value to remanufactured products and when more customers enter the green segment. The opposite is observed with a larger d_r.

As the model with two customer segments is analytically intractable, we conduct a numerical study to generate results using the same range of parameter values as in the main model. We find that the key insights continue to hold in this setting. In particular, when the existence of green customers makes remanufactured products more attractive, it contracts the area where having servicizing facilitates the adoption of remanufacturing by allowing a larger $C_r(k_r, k_n, c_n)$ and a smaller $C_s(k_r, k_n, c_n, \gamma)$. Nevertheless, we still observe the existence of the area with differentiated valuations for remanufactured products.

Further, when a green segment expands the remanufacturing market, it leads to a larger remanufacturing cost reduction effect, if present, when adopting servicizing is profitable. This observation extends the finding of remanufacturing as a marketing strategy (Atasu et al. 2008) to the circular economy context, such that the benefit of labeling remanufactured products as green can spill over to other circular strategies like servicizing.

However, as discussed in §5.2, remanufactured products are not always environmentally friendly when considering their use impact. Thus, if green customers are misled by companies' emphasis on the manufacturing phase savings of remanufacturing while neglecting the potential increase in the use impact, they may unintentionally contribute to greater environmental impact by using more remanufactured products, exacerbating the misalignment between economic and environmental goals.

EC.9. Analysis of Servicizing Remanufactured Products

In this extension, we assume that the firm servicizes remanufactured products. Under this assumption, the firm can (i) sell new products (Model N′), (ii) sell both new and remanufactured products (Model NR′), or (iii) sell new products and servicize remanufactured products (Model NS′).

Model N′ and Model NR′ are identical to Model N and Model NR in the main paper. Note that under Model NS′, costs of producing and operating a servicized product are c_r and k_r, respectively. While the customers' utility functions under this model are the same as those under Model NS in the main paper, the firm's profit function becomes:

$\Pi^{NS'} = Q_n^{NS'}(p_n^{NS'} - c_n) + \Omega_s^{NS'}(k_s^{NS'} - k_r) - \hat{Q}_s^{NS'} c_r$, where $\hat{Q}_s^{NS'} = \Omega_s^{NS'}/\gamma$.

We solve $Model\ NS^{'}$ under the same assumptions stated in the paper. Lemma EC.1 below provides the expressions for optimal prices under $Model\ NS'$.

Lemma EC.1. *The optimal prices under $Model\ NS'$ are as follows:*
$k_s^{NS'^*} = \frac{\gamma(6k_n - 2k_r + 1) - 2c_r + X}{5\gamma}$*, and* $p_n^{NS'^*} = \frac{(k_s^{NS'^*} - k_n)[(k_s^{NS'^*} - k_n)(2 - 2k_s^{NS'^*} + A)\gamma + c_s(k_s^{NS'^*} - k_n + 2c_n\gamma)]}{2[c_r + (k_s^{NS'^*} - k_n + A)\gamma]}$*, where* $A = (k_r - k_n)$*,* $B = (1 - k_r)$*, and*
$Y' = \sqrt{24c_r^2 + 16c_r\gamma(4A + B) - \gamma^2(1 - 10c_n + 24k_r^2 + 41k_n^2 + 16k_r - 18k_n - 64k_nk_r)}$.

We can derive the conditions under which adopting $Model\ NS'$ results in a higher profit than $Model\ NR^{'}$ (whose optimal solution is given in Lemma EC.5.1) in Proposition EC.2. In this extension, some expressions in the proofs are omitted due to complexity ($\Delta\Pi$, $\Delta\Pi_2$, ΔQ_r, and ΔE) but are available upon request.

Proposition EC.2. *When* $c_r < \min\left\{C_r(k_r, k_n, c_n), C_r'(k_r, k_n, c_n, \gamma)\right\}$ *and* $\gamma > \Gamma'(k_r, k_n, c_n, c_r)$*, $Model\ NS'$ is strictly preferred to $Model\ NR'$ in terms of profit.*

Proof of Proposition EC.2: We know from Proposition 2 in the main paper that if $c_r < C_r(k_r, k_n, c_n) = \frac{1}{6}\left(-4(k_r - k_n)\sqrt{6c_n + 7k_n^2 - 2k_n(6k_r + 1) + 6k_r^2 + 1} + 6c_n + 11k_n^2 - 20k_nk_r - 2k_n + 9k_r^2 + 2k_r\right)$, $Q_r^{NR'^*} > 0$. Using optimal prices derived in Lemma EC.1, we obtain $Q_s^{NS'^*} = \frac{6(3c_r + 4\gamma A + \gamma B) - 4Y'}{5\gamma}$. Therefore, we can derive the sufficient condition for $Q_s^{NS'^*} > 0$ as $c_r < C_r'(k_r, k_n, c_n, \gamma) = \frac{\gamma}{3}[2\sqrt{6c_n + (1 - k_n)^2} - (1 + 3k_r - 4k_n)]$. Thus, when $c_r < \min\left\{C_r(k_r, k_n, c_n), C_r'(k_r, k_n, c_n, \gamma)\right\}$, $Model\ NR'$ and $Model\ NS'$ exist. With this condition, we can obtain the profit difference $\Delta\Pi$ as $(\Pi^{NS'^*} - \Pi^{NR'^*})$. We have $\frac{\partial \Delta\Pi}{\partial \gamma} > 0$; that is, $\Delta\Pi$ always increases in γ. Let $\Gamma'(k_r, k_n, c_n, c_r)$ be the γ value at which $\Pi^{NS'^*} = \Pi^{NR'^*}$. Obtaining the expression for $\Gamma(k_r, k_n, c_n, c_r)$ is analytically challenging, but we numerically observed that it could be positive or negative. When $\Gamma'(k_r, k_n, c_n, c_r) < 0$, it is evident that for any given $\gamma > 0$, we have $\Pi^{NS'^*} > \Pi^{NR'^*}$. When $\Gamma'(k_r, k_n, c_n, c_r) > 0$, then $\Pi^{NS'^*} > \Pi^{NR'^*}$ only if $\gamma > \Gamma'(k_r, k_n, c_n, c_r)$. This completes the proof. □

Given that $Model\ NR'$ and $Model\ NS'$ exist, servicizing remanufactured products becomes more profitable relative to selling when pooling is high. We further observed that $\Gamma'(k_r, k_n, c_n, c_r)$ decreases in c_r. This is because increasing remanufacturing costs negatively affects the profitability of both models and being able to pool remanufactured products effectively reduces the negative impact on $Model\ NS'$. Thus, an increase in c_r reduces $\Gamma'(k_r, k_n, c_n, c_r)$ required for $Model\ NS'$ to be more profitable than $Model\ NR'$. For a given γ, this is equivalent to having a c_r lower bound for adopting $Model\ NS'$. That is, the joint adoption of servicizing and remanufacturing is dominant when the remanufacturing cost is neither too high nor too low. Thus, the qualitative insights regarding the joint adoption decision (Proposition 3) in the main model continue to hold.

Next, we compare $Model\ NS'$ with $Model\ NR'$ regarding their environmental impact. As a direct comparison is analytically challenging, we resort to a numerical study. For ease of comparison with the main paper, we restrict our attention to the condition under which $Model\ NS'$ is strictly more profitable than $Model\ NR'$. With the remanufacturing cost (c_r) as the x-axis, Figure EC.2a below compares the number of remanufactured products of both models, and Figure EC.2b traces the contrasting trajectories of environmental impact change due to the joint adoption ($\Delta E = (E^{NS'} - E^{NR'})/E^{NR'}$). A positive percent change ($\Delta E > 0$) means an increase in the environmental impact after the joint adoption.

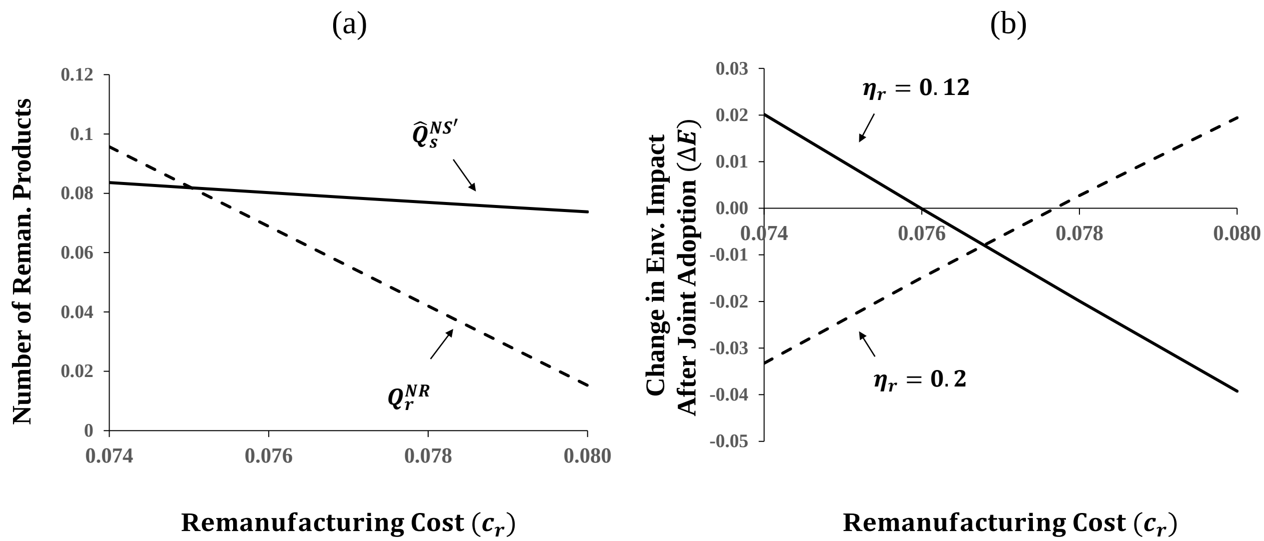

Figure EC.2 **Impact of the Joint Adoption Decision on the Average Environmental Impact.** $k_r = 0.14$, $k_n = 0.1$, $c_n = 0.1$, $\gamma = 0.5$, $\delta_n = 0.1$, $\delta_r = 0.05$, $\eta_n = 0.1$.

The intuition behind the figure is similar to that of Proposition 4 in the main paper. When c_r is low, the number of remanufactured products under $Model\ NS'$ is lower than that under $Model\ NR'$. As c_r increases, the number of remanufactured products decreases under both models, with a lower decreasing rate under $Model\ NS'$ due to effective pooling. Consequently, when the remanufacturing cost is sufficiently high, $\hat{Q}_s^{NS'} > Q_r^{NR'}$, and the difference enlarges as c_r further increases (Figure EC.2a). Whether the joint adoption lowers the environmental impact then depends on the environmental performance of remanufactured products relative to their new counterparts. If remanufacturing leads to substantial savings of materials and energy in the manufacturing phase and does not render a significantly higher use impact (the $\eta_r = 0.12$ line Figure EC.2b), more remanufactured products in the market can eventually make $Model\ NS'$ environmentally superior to $Model\ NR'$ (the descending trend of the $\eta_r = 0.12$ line as c_r increases). In contrast, when products incur a much higher use impact after being remanufactured, adopting $Model\ NS'$ can result in a higher environmental impact when it increases the number of remanufactured products in the market (the growing trend of the $\eta_r = 0.2$ line in Figure EC.2b).

EC.9.1. Servicizing the New, or the Remanufactured?

One might wonder how $Model\ NS'$ compares with $Model\ NRS$ in the main paper. The firm's decision, instead of whether to jointly adopt servicizing and remanufacturing, now becomes whether to servicize new or remanufactured products. Proposition EC.3 formalizes the results.

PROPOSITION EC.3. *When $Model\ NS'$ and $Model\ NRS$ both exist, and $c_r < C'_{r2}(k_r, k_n, c_n, c_s, \gamma)$, $Model\ NS'$ is strictly preferred over $Model\ NRS$ in terms of profit.*

Proof of Proposition EC.3: when $Model\ NS'$ and $Model\ NRS$ both exist (please refer to proofs for Proposition EC.2 and Proposition 3 for conditions under which both models exist), we can obtain the profit difference $\Delta\Pi_2$ as $(\Pi^{NS'^*} - \Pi^{NRS*})$. We have $\frac{\partial \Delta\Pi_2}{\partial c_r} < 0$; that is, $\Delta\Pi_2$ always decreases in c_r. Let $C'_{r2}(k_r, k_n, c_n, c_s, \gamma)$ be the c_r value at which $\Pi^{NS'^*} = \Pi^{NRS*}$. Obtaining the expression for $C'_{r2}(k_r, k_n, c_n, c_s, \gamma)$ is analytically challenging, but we numerically observed that it could be positive or negative. When $C'_{r2}(k_r, k_n, c_n, c_s, \gamma) < 0$, for any given $c_r > 0$, we have $\Pi^{NS'^*} < \Pi^{NRS*}$. When $C'_{r2}(k_r, k_n, c_n, c_s, \gamma) > 0$, then $\Pi^{NS'^*} > \Pi^{NRS*}$ only if $c_r < C'_{r2}(k_r, k_n, c_n, c_s, \gamma)$. This completes the proof. □

Proposition EC.3 shows that servicizing remanufactured products is more profitable than servicizing new products when the remanufacturing cost in $Model\ NS'$ is sufficiently low. We further observe that $C'_{r2}(k_r, k_n, c_n, c_s, \gamma)$ increases with c_s. Our analysis implies that when the remanufacturing cost reduction effect is not salient in $Model\ NRS$ such that c_s is relatively high, $C'_{r2}(k_r, k_n, c_n, c_s, \gamma)$ is also high, and $Model\ NS'$ is more likely to be more profitable than $Model\ NRS$.

Proposition EC.4 presents the conditions under which $Model\ NS'$ is environmentally superior to $Model\ NRS$.

PROPOSITION EC.4. *When $Model\ NS'$ and $Model\ NRS$ both exist, $Model\ NS'$ results in a lower environmental impact compared to $Model\ NRS$ when*
(1) $c_r < C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$ and $\delta_r < \Delta'(k_r, k_n, c_n, c_r, c_s, \gamma, \delta_n, \eta_n, \eta_r)$, or
(2) $c_r > C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$ and $\delta_r > \Delta'(k_r, k_n, c_n, c_r, c_s, \gamma, \delta_n, \eta_n, \eta_r)$.

Proof of Proposition EC.4: when $Model\ NS'$ and $Model\ NRS$ both exist. Let $\Delta Q_r = \hat{Q}_s^{NS'*} - Q_r^{NRS*}$. Then we have $\frac{\partial \Delta Q_r}{\partial c_r} < 0$. Therefore, ΔQ_r always decreases in c_r. Let $C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$ be the c_r value at which $\Delta Q_r = 0$. When $c_r < C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$, we have $\hat{Q}_s^{NS'*} > Q_r^{NRS*}$. We next construct ΔE as

$(E^{NS'^*} - E^{NRS*})$. Then we know $\frac{\partial \Delta E}{\partial \delta_r} = \Delta Q_r$. Thus, when $c_r < C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$, we have $\frac{\partial \Delta E}{\partial \delta_r} > 0$. That is, ΔE increases in δ_r. When $c_r > C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$, we have $\frac{\partial \Delta E}{\partial \delta_r} < 0$. That is, ΔE decreases in δ_r. Let $\Delta'(k_r, k_n, c_n, c_r, c_s, \gamma, \delta_n, \eta_n, \eta_r)$ be the δ_r value at which $(E^{NS'^*} = E^{NRS*})$. Then when $c_r < C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$ and $\delta_r < \Delta'(k_r, k_n, c_n, c_r, c_s, \gamma, \delta_n, \eta_n, \eta_r)$, $\Delta E < 0$, and vice versa. This completes the proof. □

As shown in Proposition EC.4, the qualitative insights in Proposition 4 in the main paper continue to hold. To explain, when $c_r < C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$, we have $\hat{Q}_s^{NS'} > Q_r^{NRS}$. Thus, a substantial decrease in the manufacturing impact of remanufactured products ($\delta_r < \Delta'(k_r, k_n, c_n, c_r, c_s, \gamma, \delta_n, \eta_n, \eta_r)$) can make *Model NS'* more environmentally sustainable than *Model NRS*. On the contrary, when $c_r > C'_{r3}(k_r, k_n, c_n, c_s, \gamma)$, or $\hat{Q}_s^{NS'} < Q_r^{NRS}$, the same type of remanufactured products now favors the adoption of *Model NRS* over *Model NS'* concerning environmental performance.

Summarizing the insights above, we can conclude that servicizing remanufactured products is a superior strategy compared to servicizing new products in both economic and environmental performance when the cost of remanufacturing a previously sold product is sufficiently low, and remanufactured products are more environmentally friendly compared to new ones in terms of their combined manufacturing and use impacts.

EC.10. Alternative Formulation of Remanufacturing Cost with Servicizing

In our analysis so far, we assumed that the average remanufacturing cost c_s when servicizing is offered is independent of the number of new and servicized cores available. In reality, firms may prioritize cores with lower remanufacturing costs, and the average remanufacturing cost depends on the number of servicized cores used relative to new product cores. In this extension, we assume that the remanufacturing cost of a previously-servicized unit is c'_s, and the remanufacturing cost of a previously-sold unit is c'_r. It is evident that the firm will prioritize remanufacturing using servicized cores when $c'_s \leq c'_r$ and prefer new product cores when $c'_s > c'_r$. Therefore, the firm's objective function becomes:

$$\begin{aligned} \underset{p_n \geq 0, p_r \geq 0, k_s \geq 0}{\text{Maximize}} \ \Pi &= Q_n(p_n - c_n) + [\Omega_s(k_s - k_n) - \hat{Q}_s c_n] + Q_r p_r - [min(\hat{Q}_s, Q_r)c'_s + (Q_r - \hat{Q}_s)^+ c'_r], \\ \text{s.t. } Q_r &\leq Q_n + \hat{Q}_s. \end{aligned} \tag{EC.1}$$

when $c'_s \leq c'_r$, and

$$\begin{aligned} \underset{p_n \geq 0, p_r \geq 0, k_s \geq 0}{\text{Maximize}} \ \Pi &= Q_n(p_n - c_n) + [\Omega_s(k_s - k_n) - \hat{Q}_s c_n] + Q_r p_r - [min(Q_n, Q_r)c'_r + (Q_r - Q_n)^+ c'_s], \\ \text{s.t. } Q_r &\leq Q_n + \hat{Q}_s. \end{aligned} \tag{EC.2}$$

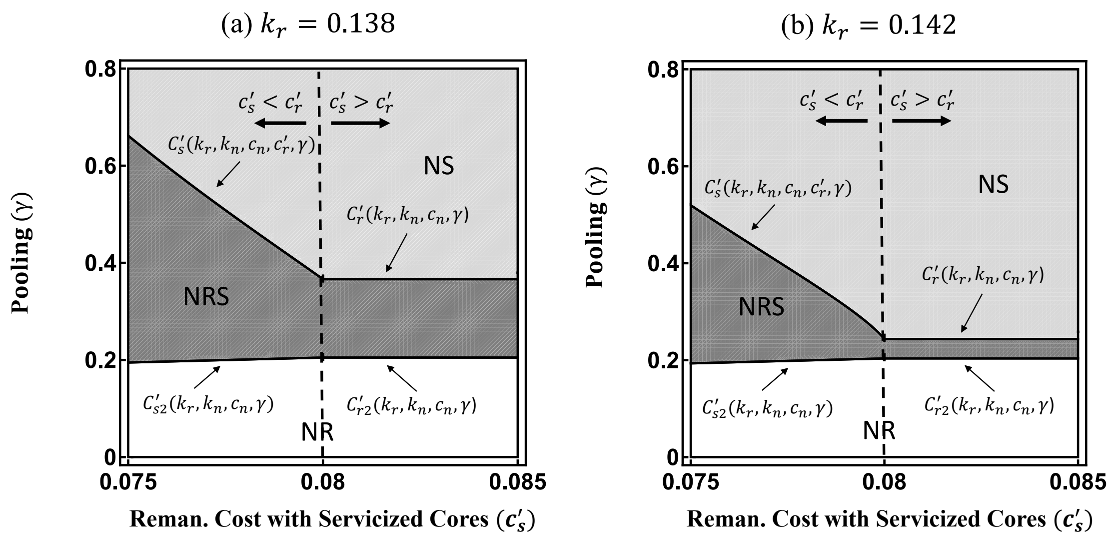

Figure EC.3 **Joint Adoption Decision (Alternative Formulation of Remanufacturing Cost with Servicized Cores).** $k_n = 0.1$, $c_n = 0.1$, $c'_r = 0.08$.

when $c'_s > c'_r$.

Figure EC.4 illustrates the environmental impact of the joint adoption compared to that of Model NR and Model NS. It is evident that the results are consistent with the key findings derived from Proposition 4 and Figure 3.

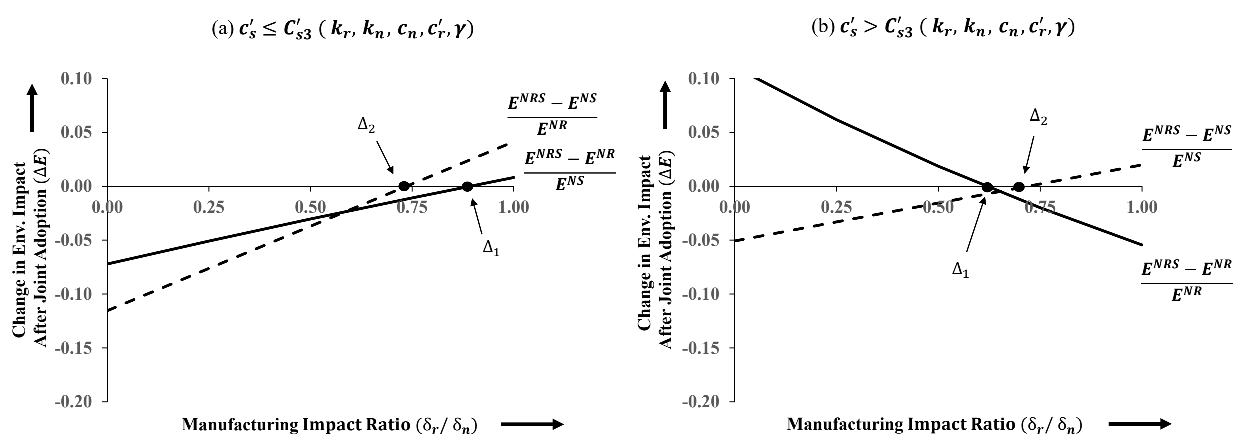

Figure EC.4 **Impact of Joint Adoption on the Average Environmental Impact (Alternative Formulation of Remanufacturing Cost with Servicized Cores).** $\gamma = 0.6$, $\delta_n = 0.1$, $\eta_n = 0.1$, $\eta_r = 0.12$

Obtaining analytical results for all possible conditions in this case is challenging. Therefore, we resort to a numerical study to check the main results. Figure EC.3 plots the area of adopting S&R jointly using the same parametric setting as in Figure 2. We find that the key insights in the main paper still hold. For example, the firm adopts remanufacturing in isolation when pooling is low and adopts servicizing in isolation when pooling is high; the joint adoption region expands then shrinks as pooling increases and shrinks as the remanufactured products-related costs increase; the condition for the joint adoption becomes restrictive when the remanufacturing cost of servicized cores is higher than that of new product cores ($c'_s > c'_r$).

Observe that the joint adoption region remains the same when $c'_s > c'_r$. This is because when Model NR exists (which is the case under the parametric setting in Figure EC.3), adopting servicizing when $c'_s > c'_r$ will lead to fewer remanufactured products in the market due to the absence of remanufacturing cost reduction effect (numerically observed and verified). In this case, the number of remanufactured products will not exceed the number of new products after adopting servicizing, and thus, servicized cores will not be used for remanufacturing, rendering c'_s irrelevant when $c'_s > c'_r$.

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