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INTEGRATED PRICING AND PRODUCTION PLANNING FOR REMANUFACTURING

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Abstract. *Appropriate pricing and production planning plays a key role in optimizing remanufacturing. Buy-back price of an end-of-life product enables to manage the quantity and quality of supply, while selling price of a remanufactured product allows to control demand. Production planning makes it possible to match the supply and demand at the minimum cost. This paper addresses the issue that such pricing and production planning should be optimized in an integrated manner to maximize the profit from remanufacturing but they have been dealt with separately. A model for integrated pricing and production planning is proposed which maximizes the profit from remanufacturing by matching the supply and demand at the part level. The model is applied to an example of smartphone remanufacturing for illustration.*

Keywords: Remanufacturing, End-of-life recovery, Pricing, Production planning

1. **Introduction.** Remanufacturing is the ultimate form of recovery that recycles not only the raw materials but also the value-added during the manufacturing process [1]. In remanufacturing, an end-of-life product is taken back and disassembled into parts, and reusable parts are harvested and reused to make another product, called remanufactured product [2,3]. In general, remanufactured products are regarded as an effective alternative to the original products with lower price and better environmental sustainability.

Remanufacturing requires both the supply of end-of-life products and the demand for remanufactured products. Matching the supply and demand is critical to maximize the profits from remanufacturing [4]. Appropriate pricing and production planning play a key role in achieving this goal. Buy-back price of an end-of-life product (i.e., a financial incentive for returning an end-of-life product) is an effective means for controlling the supply of end-of-life products [5]. Selling price of a remanufactured product is an effective strategy to control demand. Production planning links the supply and demand. It helps to achieve the required level of production with the existing resources, at the minimum cost.

This paper addresses the issue that pricing and production planning in remanufacturing should be optimized in an integrated manner to maximize the profit but they have been dealt with separately. Although extensive literature exists on the pricing for remanufacturing, most studies have focused on optimizing either buy-back prices for end-of-life products [6,7] or selling prices for remanufactured products [8-11]. They have ignored the fact that the per-unit production cost of remanufactured products is a function of the quantity and quality of end-of-life products as well as the quantity of remanufactured products, and thus is affected by both prices [12]. Guide et al. (2003) [4] is an exception that considered both prices simultaneously, but the process of remanufacturing (from disassembly through reconditioning to reassembly) was not fully modeled, which makes the model match the supply and demand at the product level (i.e., to produce

N remanufactured products, N end-of-life products should be returned) not at the part level.

The research in the area of production planning focuses on optimizing the logistics in the remanufacturing process. Usually, the prices of end-of-life and remanufactured products are as parameters, not as decision variables to optimize [13,14]. An exception can be found in Kwak and Kim (2013) [15]. The authors optimized both the selling price and production planning for remanufacturing; however, buy-back prices were given as parameters. Kwak et al. (2013) [16] is another exception that aimed at optimizing buy-back prices, selling prices, and production plannings for remanufactured products. However, their model considered products with a two-level structure (i.e., a product and its subordinate parts), which makes the production planning too simple to apply to generic products.

This paper proposes a new model for integrated pricing and production planning for remanufacturing. The model maximizes the profit from remanufacturing by matching the supply and demand at the part level. It consists of three components as follows.

- Buy-back pricing: determine the quantity and quality of end-of-life products to take back, which in turn decides the quantity and type of reusable parts (i.e., supply).
- Remanufacturing pricing: determine the quantity to remanufacture (i.e., demand).
- Production planning: determine the plans for product disassembly and part reconditioning, and the quantity and type of parts to externally procure for reassembly (i.e., matching the supply and demand at the minimum cost).

2. Mathematical Model.

This section describes the proposed model for integrated production planning and pricing in remanufacturing. The model assumes a generic three-level product. The nomenclature of variables and parameters are given as follows.

Nomenclature

I = Index set for level-1 product (quality level), $i \in I$.
J = Index set for level-2 part, $j \in J$.
J_c, J_o = Index set for level-2 part with and without a child part, respectively.
K = Index set for level-3 part, $j \in J$ (K_j = Index set for part j's child k).
P_i, P_r = Prices for end-of-life product i and remanufactured product, respectively.
X_i^t, X_i^m, X_i^d = Amount of product i that should be taken back, recycled, and disassembled.
$X_{j,w}^m$, $X_{j,n}^m$ = Amount of working and non-working part j to be recycled, respectively.
$X_{j,w}^d$, $X_{j,n}^d$ = Amount of working and non-working part j to be disassembled, respectively.
$X_{j,w}^c$, $X_{k,w}^c$ = Amount of working parts j and k that should be reconditioned, respectively.
$X_{k,w}^m$, $X_{k,n}^m$ = Amount of working and non-working part k to be recycled, respectively.
Y_k = Amount of brand-new part k that should be externally purchased.
Z_j, Z_r = Amount of remanufactured part j and product to produce, respectively.
c_i^d, c_j^d = Cost of disassembling a unit of product i and part j, respectively.
c_i^m, c_j^m, c_k^m = Cost of recycling a unit of product i, parts j and k, respectively.
c_j^c, c_k^c = Cost of reconditioning a unit of parts j and k, respectively.
c_j^s, c_k^s = Cost of purchasing a unit of brand-new parts j and k, respectively.
c_r^a, c_j^a = Cost of assembling a unit of remanufactured product and part j, respectively.
A_i = Amount of end-of-life product i that is available for take-back.
$s_i(P_i)$ = Take-back rate of end-of-life product i given the buy-back price of P_i.
Q = Market size (in unit of product) for the remanufactured product.
$d(P_r)$ = Demand (or, probability of purchase) for the remanufactured product.
$\mu_{i,j}$ = Disassembly yield rate; number of reusable part j obtainable from product i.

$\mu^w_{j,k}$, $\mu^n_{j,k}$ = Number of reusable part k from working and non-working part j, respectively.

$\bar{P}_i$, $\bar{P}_r$ = Maximum prices for product i and the remanufactured product, respectively.

The objective function is modeled in Equation (1). It is to maximize the profit from remanufacturing, i.e., the total revenue less the total remanufacturing cost including both the costs of take-back and remanufacturing operations. The total operation cost is the sum of five cost components: cost for disassembly (C_1), cost for material recycling (C_2), cost for part reconditioning (C_3), cost for spare procurement (C_4), and cost for reassembly (C_5).

$$\begin{aligned}
&\text{maximize}: \ P_r \cdot Z_r - \left(\textstyle\sum_{i\in I} P_i \cdot X^t_i + \sum_{n=1}^{5} C_n\right)\\
&\text{where}\\
&C_1 = \textstyle\sum_{i\in I} c^d_i \cdot X^d_i + \sum_{j\in J_c} c^d_j \cdot \left(X^d_{j,w} + X^d_{j,n}\right)\\
&C_2 = \textstyle\sum_{i\in I} c^m_i \cdot X^m_i + \sum_{j\in J} c^m_j \cdot \left(X^m_{j,w} + X^m_{j,n}\right) + \sum_{k\in K} c^m_k \cdot \left(X^m_{k,w} + X^m_{k,n}\right)\\
&C_3 = \textstyle\sum_{j\in J} c^c_j \cdot X^c_{j,w} + \sum_{k\in K} c^c_k \cdot X^c_{k,w}\\
&C_4 = \textstyle\sum_{j\in J_o} c^s_j \cdot Y_j + \sum_{k\in K} c^s_k \cdot Y_k\\
&C_5 = c^a_r \cdot Z_r + \textstyle\sum_{j\in J_c} c^a_j \cdot Z_j
\end{aligned} \tag{1}$$

Equation (2) represents the constraints of the model. Constraint g_1 limits the amount of available end-of-life products when the buy-back price is set at P_i. (Here, i represents different quality levels). Constraint g_2 prevents the quantity remanufactured from exceeding the market demand, where the demand is determined by the selling price P_r.

Constraints h_1 through h_{10} restrain the input-output flow balance in remanufacturing operations. Constraint h_1 requires every collected end-of-life product is either recycled for material recovery or disassembled for part recovery. Constraints h_2 and h_3 ensure the flow balance of level-2 parts with no child parts. After being disassembled from level-1 product, a working part j is either recycled or reconditioned, while a non-working part j is always recycled. Constraints h_4 and h_5 force the flow balance of level-2 parts with a child part. They are similar to h_2 and h_3, but further disassembly to recover level-3 parts is considered in addition. The follow balance of the level-3 part k is modeled in Constraints h_6 and h_7, for working and non-working parts, respectively. Only working parts are allowed for part reconditioning. Constraints h_8 and h_9 require that a sufficient number of level-2 parts should be prepared to remanufacture Z_r units of level-1 product. Similarly, Constraint h_{10} restrains that enough part k should be supplied in remanufacturing its parent j. Spare procurement is allowed only if the part has no child part, i.e., part j in J_o and part k. Otherwise, all necessary parts are obtained through reconditioning or remanufacturing. Finally, the rest of the constraints represents variable conditions.

$$\begin{aligned}
&g_1: X^t_i \le A_i \cdot s_i(P_i) \quad \forall i \in I\\
&g_2: Z_r \le Q \cdot d(P_r)\\
&h_1: X^t_i = X^m_i + X^d_i \quad \forall i \in I\\
&h_2: \textstyle\sum_{i\in I} \mu_{i,j} \cdot X^d_i = X^m_{j,w} + X^c_{j,w} \quad \forall j \in J_o\\
&h_3: \textstyle\sum_{i\in I} (1-\mu_{i,j}) \cdot X^d_i = X^m_{j,n} \quad \forall j \in J_o\\
&h_4: \textstyle\sum_{i\in I} \mu_{i,j} \cdot X^d_i = X^m_{j,w} + X^c_{j,w} + X^d_{j,w} \quad \forall j \in J_c\\
&h_5: \textstyle\sum_{i\in I} (1-\mu_{i,j}) \cdot X^d_i = X^m_{j,n} + X^d_{j,n} \quad \forall j \in J_c\\
&h_6: \mu^w_{j,k} \cdot X^d_{j,w} + \mu^n_{j,k} \cdot X^d_{j,n} = X^m_{k,w} + X^c_{k,w} \quad \forall j \in J_c, \forall k \in K_j\\
&h_7: \left(1-\mu^w_{j,k}\right) \cdot X^d_{j,w} + \left(1-\mu^n_{j,k}\right) \cdot X^d_{j,n} = X^m_{k,n} \quad \forall j \in J_c, \quad \forall k \in K_j\\
&h_8: Z_r = X^c_{j,w} + Y_j \quad \forall j \in J_o
\end{aligned} \tag{2}$$

$$h_9 : Z_r = X^c_{j,w} + Z_j \quad \forall j \in J_c$$
$$h_{10} : Z_j = X^c_{k,w} + Y_k \quad \forall j \in J_c, \quad \forall k \in K_j$$
$$0 \le P_r \le \bar{P}_r; \quad 0 \le P_i \le \bar{P}_i \quad \forall i \in I$$
$$X^m_i, X^m_{j,w}, X^m_{j,n}, X^m_{k,w}, X^m_{k,n} \ge 0 \quad \forall j \in J$$
$$X^t_i,\ X^d_i,\ X^c_{j,w},\ X^c_{k,w},\ Y_j,\ Y_k,\ Z_r \ge 0 \text{ and integer } \forall j \in J$$
$$X^d_{j,w},\ X^d_{j,n},\ Z_j \ge 0 \text{ and integer } \forall j \in J_c$$

3. **Example: Smartphone Remanufacturing.** In this section, a case study with an example of smartphone is presented for illustration. Figure 1 shows the smartphone (level 1) under consideration, assumed based on [17]. It consists of six level-2 parts, and three of them (top screen, dock connector, and rear panel assemblies) have level-3 child parts. Two nominal quality levels are considered for end-of-life smartphone, i.e., high ($i = 1$) and low ($i = 2$).

Figure 2 presents assumptions on the supply (take-back rate) and demand (purchase probability), i.e., how they change depending on prices. Linear functions were assumed, and the maximum prices were set at \$180, \$100, and \$440, for high-quality end-of-life, low-quality end-of-life, and remanufactured phones, respectively. The availability of end-of-life products, A_1 and A_2, were assumed as 3,000 and 5,000 units, respectively, and Q was assumed as 5,000 units. All other parameters were assumed according to [17]. They are not shown here due to the limit of space but available upon request.

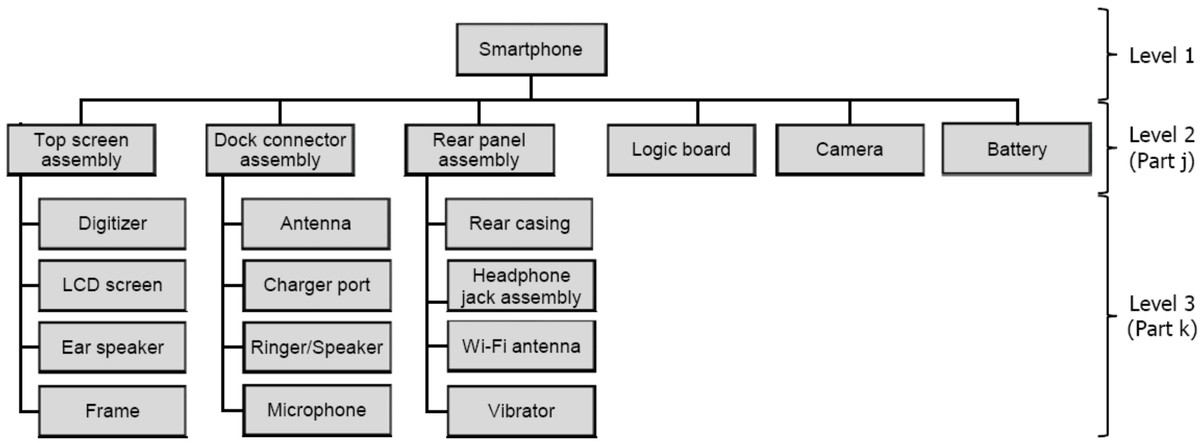

FIGURE 1. Product structure and part level definition (redrawn from [17])

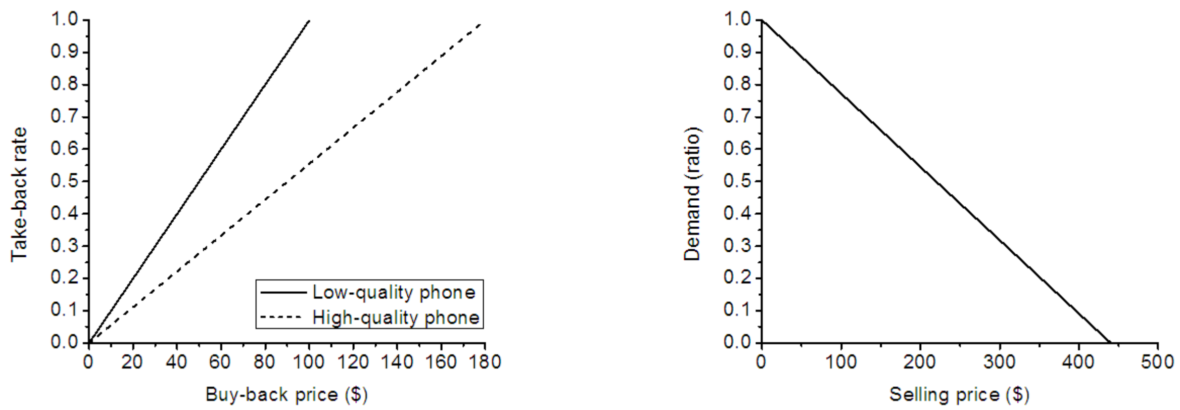

FIGURE 2. Take-back rate (left) and demand (right) depending on prices

The problem was solved using the OptQuest Solver in the Analytical Solver Platform. It is a metaheuristic solver that finds a globally optimal (or near-optimal) solution [18]. The result indicates that the optimal take-back plan is to collect 753 units of high-quality phones and 1490 units of low-quality phones by paying $45.18 and $29.8, respectively. This corresponds to the take-back rates of 25.1% and 29.8%. After take-back, all units should be disassembled into level-2 parts, and the resulting parts should follow the processing plan in Table 1. Through the processing plan, 683, 75, and 285 units of top screen, dock connector, and rear panel assemblies are remanufactured, and a total of 1,932 units of level-1 product are produced. The optimal selling price for the remanufactured product is set at $269.98, which implies 38.6% of purchasing probability, or, 1,932 units.

Table 1. Optimization result (objective value: $4111.82)

Part	$X^d_{j,w}$	$X^d_{j,n}$	$X^c_{j,w}$, $X^c_{k,w}$	$X^m_{j,w}$, $X^m_{k,w}$	$X^m_{j,n}$, $X^m_{k,n}$	Y_k	Z_j
Top screen assembly	0	993	1249	0.17	0.83	·	683
Dock connector assembly	0	206	1857	0.09	179.91	·	75
Rear panel assembly	0	595	1647	0.00	1.00	·	285
Logic board	·	·	1932	2.57	308.43	0	·
Camera	·	·	1925	0.63	317.37	7	·
Battery	·	·	1932	1.08	309.92	0	·
Digitizer	·	·	377	0.34	615.66	306	·
LCD screen	·	·	541	0.19	451.82	142	·
Ear speaker	·	·	683	29.97	280.03	0	·
Frame	·	·	683	115.37	194.63	0	·
Antenna	·	·	75	45.92	85.08	0	·
Charger port	·	·	75	0.19	130.81	0	·
Speaker	·	·	75	49.84	81.16	0	·
Microphone	·	·	75	45.92	85.08	0	·
Rear casing	·	·	242	0.16	352.84	43	·
Headphone jack assembly	·	·	284	0.41	310.59	1	·
Wi-Fi antenna	·	·	285	10.12	299.88	0	·
Vibrator	·	·	285	10.12	299.88	0	·

4. **Future Work.** In this paper, a model for integrated pricing and production planning was proposed which maximizes the profit from remanufacturing by matching the supply and demand at the part level. Future work may involve extending the current model to deal with a portfolio of new and remanufactured products. Other future work would be to include consideration of environmental impact of remanufacturing.

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