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In-House Refurbishing and Outsourcing Refurbishing Models with Degree of Interchangeability in Product Design

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ABSTRACT

Refurbishing is the process of processing used products into products with the quality of new products. Refurbishing can be done by the manufacturer itself (in-house) or the manufacturer can delegate the refurbishing process to other manufacturers (outsourcing). This research aims to construct an in-house refurbishing model and an outsourced refurbishing model, determine the optimum solution, analysis, and application so that optimum benefits are obtained, and compare the in-house refurbishing model and the outsourced refurbishing model. Multivariable function optimization is used to get optimum profit. Judging from the optimum production results, manufacturers who carry out in-house refurbishing choose a higher degree of interchangeability and produce more new products. Products with an interchangeability design are products that can be used to replace similar products with the same function. Based on economic benefits, manufacturers who carry out in-house refurbishing get greater profits than outsourcing refurbishing. Viewed from environmental sustainability, outsourcing refurbishing is more environmentally friendly than in-house refurbishing.

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A. INTRODUCTION

Currently, numerous companies are actively engaged in the refurbishing of products. Prominent industry leaders like Apple, Samsung, Lenovo, Motorola, Dell, and HP have also entered the market for selling refurbished products (Han et al., 2022; Qin et al., 2023; Subramanian et al., 2013; Zhou et al., 2023). According to Persistent Market Research, the refurbished smartphone sector experienced an annual growth rate of 7% between 2016 and 2021, surpassing the growth rate of 3% in the new smartphone sales sector (Kumar et al., 2022). Refurbishing involves the transformation of discarded items into products that exhibit a quality comparable to new ones. The refurbishment process can be conducted either internally or externally. When a company performs the task internally, it is known as in-house refurbishment, while outsourcing involves delegating the task to third-party entities.

While interchangeable design can decrease manufacturing costs, it also diminishes product distinctiveness and fosters intense competition and cannibalization between them (Yang et al., 2023; Gong et al., 2023; Jalali et al., 2019; Atasu Daniel R Guide & Luk Van Wassenhove, 2010). One example such as the Lexus line of luxury motor vehicles from Toyota, which is renowned as one of the best-selling luxury brands in the United States. The lower-end Camry line and the Lexus line have numerous shared components. This interchangeable design has the potential to cannibalize sales for the Lexus brand. Car reviews often highlight this issue by likening it to "same perfume, different bottle." Integrating refurbishing into existing business activities would intensify cannibalization issues, particularly due to the ease of disassembling used products facilitated by interchangeable design (Fu et al., 2021; Harivardhini & Chakrabarti, 2016). This streamlined disassembly process reduces the operating costs involved and consequently lowers the prices of refurbished products. Moreover, refurbishing is commonly perceived as a restoration process that brings pre-owned items to a condition similar to new through component replacements and warranties that match or exceed those offered for new products.

The general consensus proposes that companies should aim for a harmonious combination of revenue and cost factors while incorporating interchangeable design across various product lines. (Wang et al., 2022; Wu, 2012). However, the dynamics surrounding interchangeable design become more intricate within the context of refurbishing. For instance, certain original equipment manufacturers (OEMs) tend to delegate their refurbishment operations to authorized refurbishment providers (Liu et al., 2022; Xia et al., 2023; Zou et al., 2016) or to conduct in-house refurbishing (Fang et al., 2023; Niu et al., 2022; Teng & Feng, 2021). To address the cannibalization issue arising from refurbished products offered by third-party remanufacturers (TPR), some manufacturers have modified the interchangeable design related to refurbishing. This includes implementing design for disassembly or design for modularity. Consequently, the findings regarding interchangeable design and cannibalization concerns among independent products cannot be immediately extrapolated to interchangeable design in the refurbishing context. In addition, several researchers have focused on examining the influence of government subsidies on refurbishing within various market structures (Cao et al., 2023; Chai et al., 2023; Feng & Yu, 2023; Qiao & Su, 2021; Zhao et al., 2022). The findings indicate that government subsidies directed towards refurbishers can enhance their market competitiveness. Similarly, government subsidies targeted at consumers can significantly impact the market competitiveness of refurbished products.

According to Ovchinnikov (2011) and Kurdhi et al. (2022), the availability of refurbished products at a reduced price gives rise to concerns regarding potential cannibalization of sales for higher-margin new products. Consequently, many companies choose not to offer refurbished products alongside new ones. However, incorporating both refurbished and new products in the product line up enables firms to effectively target different customer segments

And attract purchases from budget-conscious customers who favor refurbished choices. In this way, despite the potential loss of new product sales, providing a range of both new and remanufactured products can bring financial advantages to the company as a whole, provided that the pricing and quantity of refurbished items are carefully managed. The market consists of two separate customer groups: high-end and low-end. High-end customers are willing to buy new products, but they may also contemplate refurbished options. Conversely, low-end customers exclusively choose refurbished products. Both firms maintain fixed and consistent prices for their new products, and the process of refurbishing typically does not impact pricing, procurement, or other decisions related to new product offerings. As a result, the price of a particular generation of new products remains unchanged until the introduction of the next generation.

This research focuses on constructing and analyzing two distinct refurbishing models: in-house refurbishing (Model I) and outsourced refurbishing (Model O). The primary objective is to determine the optimal strategies that can maximize profits for an original equipment manufacturer (OEM) while addressing the challenges of cannibalization resulting from refurbishing. In Model I, where the OEM internally manages refurbishing operations, we delve into the strategic decisions made by the OEM regarding design interchangeability and quantity to effectively mitigate the impact of refurbished products' cannibalization. In Model O, we explore the outsourcing of refurbishing to third-party refurbishers and assess how this strategy impacts profitability. This involves evaluating the OEM's choices regarding design interchangeability and its influence on cannibalization. Additionally, this research considers the influential roles of government subsidies and consumer behavior in both models. By utilizing multivariable function optimization, we aim to identify the most favorable solutions that maximize economic benefits while also considering environmental sustainability aspects.

B. ASSUMPTIONS AND NOTATIONS

The main objective of this research is to gain a deeper comprehension of how the replaceable design philosophy of the organization affects the financial benefits of refurbishing, whether it is done internally or externally. Figure 1 demonstrates that when refurbishing is conducted independently, the corporation chooses design interchangeability for Model I. Model I is in line with the internal remodeling projects carried out by various businesses. Instead, with Model O, the manufacturer just concentrates on production while contracting third-parties to handle the refurbishing. In Model O, the manufacturer determines the prices of new and refurbished products (p_n and p_r) and the quantities of both products (q_n and q_r). In Model I, the manufacturer determines the fee (f) charged for refurbishing outsourcing. The profits of both the manufacturer and the third party can be maximized with the optimal prices and quantities of new and refurbished products. It is important to emphasize that this model can demonstrate the utilization of independent refurbishers by various companies like Apple, IBM, and Land Rover to address their refurbishment requirements. The specifics of the assumptions used in this study will now be explored, as shown in Figure 1.

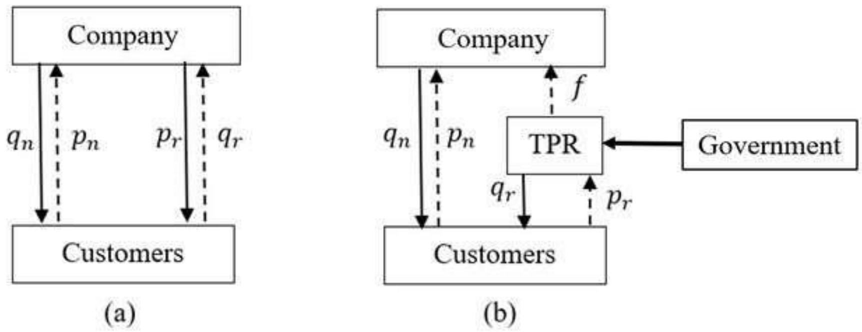

Figure 1. Two-tiered structures: (a) Model I and (b) Model O.

Assumption 1. *Because the products are interchangeable, assembly and disassembly are simple, which minimizes the cost of both manufacturing and refurbishing. To put it another way, the cost of producing a new product is* $c_n - i$*, whereas the cost of producing a product that has been previously used is* $c_r - \gamma i$*, where* $0 < \gamma < 1$ *represents the interchangeability spillover effect from the new product to the refurbished product.*

In this study, c_n and c_r refer to the manufacturing cost per base unit and the refurbishment cost per base unit at the basic level. Due to the consistently lower cost of refurbishment compared to manufacturing a new product, this study assumes that $c_r < c_n$. Since a product with great interchangeability will be effective for both making a new product and dismantling fit or refurbishing, it will immediately lower manufacturing costs for both new and refurbished products. Let's pretend that the producer decided to incorporate interchangeability into the design of their product, which would result in a new product's unit production cost of $c_n - s$ and a refurbished product's unit cost of $c_r - \gamma s$, with $0 < \gamma < 1$ standing in for the interchangeability spillover effect from the new product to the refurbished product.

We make the assumption that the cost associated with the interchangeable design is $\varphi = e_2^{i^2}$, a quadric form of *i* and that the parameter for scaling in relation to *i* is *e* > 0. In other words, we define the levels of interchangeability, i, as a function of the cost of $\varphi = e_2^{i^2}$, which stands for the cost of the design effort. We use the scaling parameter $e > 0$ to explain how investment returns decline over time.

Assumption 2. *In a single-period scenario, both spouses aim to maximize their earnings. The producer starts off by describing the level of interchangeability in product design (i) and the costs (f) connected with outsourcing refurbishing. The best units for each of the two items (i.e.,* q_n *and* q_r*) are then decided upon by the two parties.* The following Table 1 lists the relevant parameters and decision factors.

Table 1. Definitions regarding the main variables and decision variables

Variable	Definition
p_n/p_r	price of new/refurbished products
q_n/q_r	production quantity of new/refurbished products
c_n/c_r	base unit production cost of new/refurbished products
a_n/a_r	unit environmental effect of a new/remanufactured product
i	degree of interchangeability
γ	spillover effect from interchangeability design

e	scale parameters of interchangeability design costs
f	costs for refurbishing outsourced
t	government subsidies for refurbished products per unit
d	The combined effect of the price of refurbished products on demand
b	cannibalization coefficient
k	price elasticity of low-end customer demand
r	cannibalized elasticity
q	number of requests for new products when there are no refurbished products
E	Impact of production on the environment
α	proportion of high-end customers who switch from new to refurbished products

C. RESULT AND DISCUSSION

1. Model Formulation

In this part, two different models are used to study the relationship between producer and third-parties in interchangeability design. The conclusions are derived through the process of backward induction. When determining the best distribution channel for reconditioned products, the licensing plan is taken into account first. We consider a supply chain that includes a producer (refurbisher) that creates an entirely new product, as well as a third party (3P) that purchases, refurbishes, and resells used items. The producer makes an investment of c_n per unit in the development of the new product, which it then sells at a fixed price of p_n. The cost of the new product is set till the introduction of the next generation. Customers aren't urged in this scenario to wait to purchase the new product until the price has sufficiently dropped. The cost per unit of making the new product, $c_r < c_n$, is greater than the cost per unit of refurbishing the 3P, which is c_r. The 3P is free to set the reconditioned item's price at a level that will maximize its profits (p_r).

On the market, high-end and low-end products are divided into two categories. High-end customers are keen to purchase brand-new goods, in contrast to clients at the low end who only purchase refurbished goods at lower prices. When new products are needed, or when reconditioned goods are not accessible, there is a strong demand. If they are available, a portion of high-end purchasers will switch to reconditioned goods if there is a market for them. By offering a refurbished item at a price of p_r, a 3P can attract $k(p_n - p_r)$ low-end customers who won't purchase new goods. Based on Kurdhi et al. (2023), the number of customers who purchase both new and refurbished products is as follows:

$$q_n = (1 - \alpha(p_r))q \quad (1)$$
$$q_r = k(p_n - p_r) + \alpha(p_r)q \quad (2)$$

Alternatively, we assume that cannibalization is similar to a universal linear switching function, that

$$\alpha(p_r) = b(p_n - p_r) \quad (3)$$

for some coefficient b.

In this article, we discuss the best strategic choices made by both parties in a supply chain for two distinct models: Model O, where the producer manufactures both new and refurbished products, and Model G, where the producer enters into a contract with the TPR to handle the refurbishing procedures in addition to receiving government subsidies.

2. Model I

When choosing the best price for refurbished goods (p_r), the producer in model I first specifies the degree of product interchangeability (i).The producer's issue can be revealed by

$$P_I(p_r, i) = (p_n - c_n + i)q_n + (p_r - c_r + \gamma i)q_r - \frac{1}{2}ei^2. \tag{4}$$

According to Equations (1), (2), and (3), Model (4) can also express as follows:

$$\boldsymbol{P_I(p_r, i) = (p_n - c_n + i)\big(q - r(p_n - p_r)\big) + (p_r - c_r + \gamma i)\big(d(p_n - p_r)\big) - \frac{1}{2}ei^2}. \tag{5}$$

Equation 5 can be maximized using p_r and i^{I^*}. The best level of interchangeability in product design is then determined by inserting $p_r^{I^*}$ and i^{I^*} and accounting for producer revenue. The price of the refurbished product, the degree of interchangeability, the volume of new product production, the volume of refurbished product, and the producer's profit, respectively, are best values in the refurbishing in-house model. These optimal values are

$$p_r^{I^*} = \frac{-qr + dq\gamma + erc_n - dec_r + \big(r(-e+r) + d^2\gamma^2 - d(e+2r\gamma)\big)p_n}{r^2 + d^2\gamma^2 - 2d(e+r\gamma)}, \tag{6}$$

$$i^{I^*} = \frac{-2dq + (r-d\gamma)(rc_n - dc_r + (d-r)p_n)}{r^2 + d^2\gamma^2 - 2d(e+r\gamma)}, \tag{7}$$

$$q_n^{I^*} = \frac{dq\big(-2e + \gamma(-r+d\gamma)\big) + er(rc_n - dc_r + (d-r)p_n)}{r^2 + d^2\gamma^2 - 2d(e+r\gamma)}, \tag{8}$$

$$q_r^{I^*} = \frac{d(q(r-d\gamma) - erc_n + dec_r + e(-d+r)p_n)}{r^2 + d^2\gamma^2 - 2d(l+r\gamma)}, \tag{9}$$

$$\begin{aligned} P_I^*(p_r, i) = -\frac{1}{2\big(r^2 + d^2\gamma^2 - 2d(e+r\gamma)\big)} &\,(2dq^2 + lr^2c_n^2 + dc_r(2q(r - d\gamma) \\ &+dec_r) + 2d(2eq + q(-1+\gamma)(r - d\gamma) + e(-d+r)c_r)p_n \\ &+e(d-r)^2p_n^2 + 2c_n(dq(-2e - r\gamma + d\gamma^2) - derc_r + e(d-r)rp_n)). \end{aligned} \tag{10}$$

3. Model O

Similar to Model I, the producer decides how much of the product's initial design is interchangeable in Model O (i), as well as the costs, f, associated with refurbishing outsourced at the same time. producer problems are dependent on i and f. The revenue of TPR might be maximized by p_r. In this section, we analyze the impact of subsidy incentives on the refurbishing sector, specifically concentrating on the situation where the government funds the sales of refurbished goods under Model O. Given that in reality, government subsidies are regularly offered. The TPR will be granted a subsidy of t per unit for the purchase of refurbished products. The producer and TPR therefore both have to cope with the following issues:

$$P_O(i, f) = (p_n - c_n + i)q_n + q_r f - \frac{1}{2} e i^2 \quad (11)$$

$$P_T(p_r) = (p_r - c_r - f + \gamma i + t)q_r. \quad (12)$$

According to Equations (1), (2), and (3), Model 11 and 12 can also express as follows:

$$P_O(i, f) = (p_n - c_n + i)\big(q - r(p_n - p_r)\big) + d(p_n - p_r)f - \frac{1}{2} e i^2 \quad (13)$$

$$P_T(p_r) = (p_r - c_r - f + \gamma i + t)d(p_n - p_r). \quad (14)$$

With i^{O^*} and f^{O^*}, Equation (11) can be maximized. The appropriate level of interchangeability in product design is then determined by swapping i^{O^*} and f^{O^*} in order to optimize producer revenues. In Model G, the level of interchangeability, the cost of refurbished goods, and the production volumes of both new and refurbished goods are summarized:

$$p_r^{O^*} = \frac{-qr+det+dq\gamma+erc_n-dec_r+(-3de-er+r^2-2dr\gamma+d^2\gamma^2)p_n}{-4de+r^2+d\gamma(-2r+d\gamma)} \quad (15)$$

$$i^{O^*} = \frac{d\big(-4q+t(r-d\gamma)\big)+(r-d\gamma)(rc_n-dc_r+(d-r)p_n)}{-4de+r^2+d\gamma(-2r+d\gamma)} \quad (16)$$

$$f^{O^*} = \frac{(-2det+rt(r-d\gamma)-2q(r+d\gamma)+r\big(2e+\gamma(r-d\gamma)\big)c_n}{-4de+r^2+d\gamma(-2r+d\gamma)} + \frac{\big(2de-r^2+dr\gamma\big)c_r+\big(-2de+dr(-1+\gamma)\gamma+r(-2e+r-r\gamma)\big)p_n)}{-4de+r^2+d\,\gamma(-2r+d\,\gamma)} \quad (17)$$

$$q_n^{O^*} = \frac{d\big(e(-4q+rt)+q\gamma(-r+d\gamma)\big)+er(rc_n-dc_r+(d-r)p_n)}{-4de+r^2+d\gamma(-2r+d\gamma)} \quad (18)$$

$$q_r^{O^*} = -\frac{d(-qr+det+dq\gamma+erc_n-dec_r+e(d-r)p_n)}{-4de+r^2+d\gamma(-2r+d\gamma)} \quad (19)$$

$$P_O^* = -\frac{1}{2\big(-4de+r^2+d\gamma(-2r+d\gamma)\big)}(er^2c_n^2 + d(4q^2 + det^2 - 2qt(r - d\gamma) \quad (20)$$
$$+c_r(2qr - 2det - 2dq\gamma + dec_r)) + 2d(4eq + e(d - r)t + q(-1 + \gamma)(r - d\gamma)$$
$$+e(-d + r)c_r)p_n + e(d - r)^2p_n^2\,\gamma) - 2c_n(de(4q - rt) + dq\gamma(r - d\gamma)$$
$$+derc_r + er(-d + r)p\_n)).$$

4. Comparison of Optimal Outcomes

Proposition 1. *Producers who carry out refurbishing in-house produce and sell refurbished products as much as* $q_r^{I^*}$ *if the cost of producing refurbished products is* $c_r < c_r^{I^*}$ *with*

$$c_r^{I^*} = \frac{-qr+dq\gamma+erc_n+e(d-r)p_n}{de}.$$

While third parties as outsources produce and sell refurbished products as much as $q_r^{O^*}$ *in conditions of* $c_r < c_r^{O^*}$ *with*

$$c_r^{O^*} = \frac{-qr+det+dq\gamma+erc_n+e(d-r)p_n}{e}.$$

Based on the Preposition 1, the price of refurbished products is higher when refurbishing is done outsourced. The existence of outsourcing costs that need to be paid by producers causes high product prices in order to cover the outsourcing costs that have been incurred.

Proposition 2. *The price of a refurbished product in the refurbishing outsourcing model is higher than the price of a refurbished product in the refurbishing in-house model or* $p_r^{I^*} < p_r^{O^*}$ *in condition that the production cost of refurbished product is* $c_r > c_r^1$ *with*

$$c_r^1 = \frac{1}{r^4-d^3\gamma^2(3e+r\gamma)-dr^2(5e+3r\gamma)+d^2(8e^2+8er\gamma+3r^2\gamma^2)}$$
$$(8d^2eq\gamma - q(r-d\gamma)^2(r+3d\gamma) - t(2de-r^2+dr\gamma)(r^2+d^2\gamma^2-2d(e+r\gamma))$$
$$+(r-d\gamma)(e(r-3d\gamma)+\gamma(r-d\gamma)^2)(r\,c_n+(d-r)p_n)).$$

Based on the Proposition 2, the price of refurbished products is higher when *refurbishing* is done *outsourced*. The existence of *outsourcing* costs that need to be paid by producers causes high product prices in order to cover the costs of *outsourcing* that have been incurred.

Proposition 3. *The degree of interchangeability determined by the producer in the outsourced refurbishing model is lower than in the in-house refurbishing model or* $i^{I^*} > i^{O^*}$ *in the condition that the production cost of the refurbished product is* $c_r > c_r^2$ *with*

$$c_r^2 = \frac{-2det+(r-d\gamma)(-2q+rt-dt\gamma)+2erc_n+2e(d-r)p_n}{2de}.$$

Based on Proposition 3, when refurbishing is carried out by a third party, producers will decrease the level of interchangeability in their product design to minimize the impact on the sales of refurbished products. Products designed with a high degree of interchangeability will reduce production costs and refurbishing costs directly. Therefore, in the refurbishing in-house model, the manufacturer intends to use a good strategy to design its product with a high degree of interchangeability because the new product and refurbished product are produced by the manufacturer itself. Whereas in the refurbishing outsourcing model, all new products are produced by manufacturers and refurbished products are produced by third parties. To overcome competition with third parties, manufacturers opt for limited interchangeability in product design due to the potential rise in challenges associated with refurbishment when interchangeability is reduced.

Proposition 4. *The optimum quantity of new products in outsourced refurbishing is lower than in-house refurbishing or* ${q_n^I}^* > {q_n^O}^*$ *in the condition that the production cost of refurbished products is* $c_r > c_r^3$ *with*

$$c_r^3 = \frac{1}{2} d^3 e^3 r^2 (-2det + (r - d\gamma)(-2q + rt - dt\gamma) + 2erc_n + 2e(d - r)p_n)$$

In contrast, the optimum quantity of refurbished products in outsourced refurbishing is higher than inhouse refurbishing or ${q_r^I}^* < {q_r^O}^*$ *when* $c_r > c_r^4$ *with*

$$c_r^4 = \frac{1}{2} d^5 e^3 (-2det + (r - d\gamma)(-2q + rt - dt\gamma) + 2erc_n + 2e(d - r)p_n)$$

Based on the Proposition 4, when a third party takes over the *refurbishing* process, manufacturers will provide fewer new products and third parties will provide more refurbished products. Referring to Proposition 3, in the refurbishing in-house model, manufacturers develop products with increased interchangeability, resulting in reduced costs for both new and refurbished products. When the degree of interchangeability is high, the cost savings for new products outweigh the cost savings for refurbished products. As a result, manufacturers tend to pay more attention to selling new products than to *refurbishing* production. In the refurbishing outsourcing model, all third-party profits are obtained from *refurbishing* so that the third party offers a larger quantity of refurbished products to maximize profits which leads to a decline in the quantity of new products.

5. Evaluation of Economic Profitability

Proposition 5. *Producer profits are lower in* refurbishing outsourcing *compared to* refurbishing in-house *or* $P_I^* > P_O^*$ *on product cost refurbished* $c_r > c_r^5$ *with*

$$c_r^5 = \frac{d^2 e}{-2det + (r - d\gamma)(-2q + rt - dt\gamma) + 2erc_n + 2e(d - r)p_n}$$
$$(-2q^2(r - d\gamma)^2 - det^2\left(r^2 + d^2\gamma^2 - 2d(e + r\gamma)\right) + 2qt(r - d\gamma)\left(r^2 + d^2\gamma^2 - 2d(e + r\gamma)\right)$$
$$-2e(r\, c_n + (d - r)p_n)(-2det + (r - d\gamma)(-2q + rt - dt\gamma) + er\, c_n + e(d - r)p_n)).$$

Based on the Proposition 5, producers lose more when *refurbishing* is transferred to a third party. In this analysis, profits are obtained from two sources, namely sales of new products and sales of refurbished products or charging third-party service fees for refurbished products. In the refurbishing in-house model, both products are produced by one producer. Whereas in the refurbishing outsourcing model, the two products are manufactured separately by the OEM and a TPR. Therefore, competition between new and refurbished products is more fierce in the refurbishing outsourcing model. Increased cannibalization of refurbished products can reduce producer profits. On the other hand, it can make manufacturers reduce the degree of *interchangeability* in their product designs so that it leads to an increase in manufacturing costs for both products, especially for new products which results in manufacturers' decisions to reduce the rise in the manufacturing of new products. The direct cannibalization of third-party *refurbishing* resulted in a reduction in the number of new products. Instead, the refurbished product is incremented. Although manufacturers charge fees for refurbished products from third parties, the profits earned from *refurbishing* by third parties are not so high as to cover losses from selling new products. It can be concluded that the producer in the refurbishing outsourcing model loses more.

Proposition 6. *The producer's profit in the* refurbishing in-house *model is greater than the combined profit of the manufacturer and third parties in the* refurbishing outsourcing *model or* $P_I^* > P_G^*$ *in the condition that the cost of producing the product refurbished is* $c_r > c_r^6$ *with*

$$c_r^6 = \frac{1}{(r^4t + d^4t\gamma^4 - 4d^3t\gamma^2(2e + r\gamma) - 4dr(-eq + 2ert + r^2t\gamma) + 2d^2(6e^2t - 2e(q}$$
$$\frac{1}{-4rt)\gamma + 3r^2t\gamma^2) - 4de^2(r\,c_n + (d - r)p_n)))}((2d^2e^2(-2qr^5t + d^5t\gamma^4(et + 2q\gamma)$$
$$+dr^2(e(-4q^2 + 16qrt + r^2t^2) + 10qr^2t\gamma) - 3d^4t\gamma^2(4e^2t + 2e(4q + rt)\gamma$$
$$+5\mathrm{q}\mathrm{r}\gamma^2) - 4\mathrm{d}^2\mathrm{r}(2\mathrm{e}^2\mathrm{t}(3\mathrm{q} + \mathrm{rt}) + \mathrm{e}(-2\mathrm{q}^2 + 12\mathrm{qrt} + \mathrm{r}^2\mathrm{t}^2)\gamma + 5\mathrm{qr}^2\mathrm{t}\gamma^2) + 2\mathrm{d}^3$$
$$(6e^3t^2 + 4e^2t(3q + 2rt)\gamma + e(-2q^2 + 24qrt + 3r^2t^2)\gamma^2 + 10qr^2t\gamma^3) + 2e(rc_n$$
$$+(d - r)p\_n)(r^4t + d^4t\gamma^4 - 4d^3t\gamma^2(2e + r\gamma) - 4dr(-eq + 2ert + r^2t\gamma) + 2d^2$$
$$(6e^2t - 2e(q - 4rt)\gamma + 3r^2t\gamma^2) - 2de^2(r\,c_n + (d - r)p\_n)))).$$

Based on Proposition 6, it can be concluded that the refurbishing in-house model is still more profitable than the refurbishing outsourcing model even though the benefits of producers and third parties have been combined. Based on the previous proposition, the degree of *interchangeability* in refurbishing in-house is higher so that production costs can be reduced. This causes profits to be maximized. In this case, the industry will experience greater advantages from the monopolistic position of producers when offering both new and refurbished products. This strategy maximizes profits from both types of products while minimizing the negative impact of cannibalization.

6. Evaluation of Environmental Sustainability

Proposition 7. *The* refurbishing outsourcing *model is more environmentally friendly than the* refurbishing in-house *model or* $E_O^* < E_I^*$ *when the cost of producing the product is refurbished* $c_r > c_r^7$ *with*

$$c_r^7 = \frac{-2det + (r - d\gamma)(-2q + rt - dt\gamma) + 2erc_n + 2e(d - r)p_n}{2de}.$$

The impact on the environment is not only about the waste from the production of new products but also the quantity of refurbished products. Drawing from the preceding analysis, the quantity of new products supplied by producers decreases ($q_n^{I*} > q_O^{n*}$), while the quantity of refurbished products increases ($q_I^{r*} < q_O^{r*}$). It can be concluded that the resource savings from the *refurbishing* process are greater and the waste from producing new products is less in the refurbishing outsourcing model.

7. Numerical Example

The implementation of the *refurbishing* model uses parameter values taken from several sources. Based on the official information listed on the *Amazon* website on February 15, 2023, the price of *IPhone 11 Pro Max* is p_r = \$824. In general, the cost range *refurbishing* is 25 to 75% of the cost of producing a new product so that the cost of producing a new product is c_n = \$400 and the cost of producing the product refurbished c_r = \$300. There is a *spillover* effect for products with *interchangeability* γ = 0.04 design. To create a *interchangeability* design, there is a scale parameter of the *interchangeability* design cost e = 0.5. In the product market, there is competition between the sale of new products and refurbished products, resulting in cannibalization. The cannibalization effect is affected by the cannibalization coefficient b = 0.1 and the number of requests for new products when there are no refurbished products q = 100. The cannibalization elasticity for new and refurbished products is r = 10. The market demand for *low-end* customers also changes so that there is a price elasticity of k = 0.5. The government also supports *refurbishing* activities so that it provides t = \$1 for each refurbished product produced by a third party. It is assumed that the environmental impact of new products and refurbished products is a_n = 0.8 and a_r = 0.5, respectively, as shown in Figure 2.

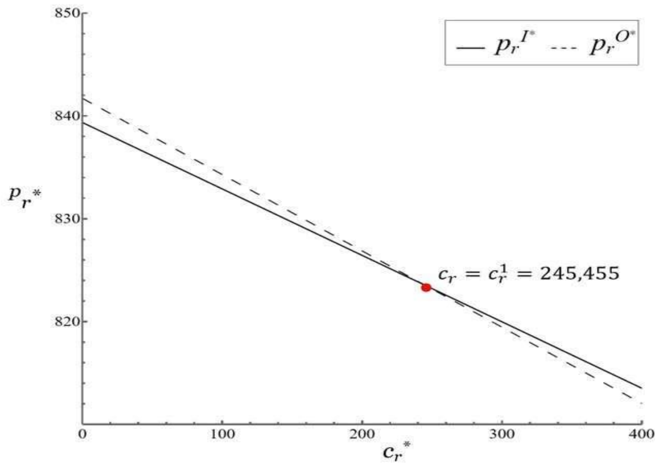

Figure 2. Variations of $p_r^{I^*}$ and $p_r^{O^*}$

Figure 2 corresponds to Proposition 2. refurbished product prices are higher when *refurbishing* is done *outsourcing* when the cost of producing refurbished product is $c_r > c_r^1$. There are intersection points on both graphs. The intersection is the condition when $c_r = c_r^1 = 245.455$. The existence of *outsourcing* costs that need to be paid by producers causes high product prices. The graph shows that when the cost of *refurbishing* (c_r) increases, the price difference for the product refurbished between the two models changes and is marked with a value of $c_r = c_r^1 = 245.455$. In addition, the greater the value of c_r, the smaller the cost of producing refurbished products in both models.

Based on Proposition 3, a manufacturer will choose a higher degree of *interchangeability* in the refurbishing in-house model than the refurbishing outsourcing model when the product costs refurbished $c_r > c_r^2$. When the cost of *refurbishing* (c_r) is getting bigger, the difference in the degree of *interchangeability* between the two models is getting bigger. In addition, the greater the value of c_r, the smaller the degree of *interchangeability* in both models. There is a similarity in the value of i when $c_r = c_r^2 = 245.455$ which can be seen in Figure 3.

Furthermore, the new product quantity graph is shown in Figure 4. It can be concluded that $q_n^{I^*} > q_n^{O^*}$ with the condition $c_r > c_r^3$. This corresponds to the Proposition 4. Producers tend to provide fewer quantities of new products in the refurbishing outsourcing model as compared to the refurbishing in-house model. As the cost of producing refurbished products (c_r) increases, the quantity of new products in both models decreases. The graph shows the intersection when the product production costs refurbished $c_r = c_r^3 = 245.455$ which indicates the same value of q_n.

Referring to the Proposition 4, producers tend to provide less refurbished products in the refurbishing in-house model than the refurbishing outsourcing model. As the cost of producing refurbished products (c_r) increases, the quantity of refurbished products in both models increases. There is a similarity in the value of $q_r^{I^*}$ and $q_r^{O^*}$, namely when the product production cost is refurbished $c_r = c_r^4 = 245.455$. The difference in the quantity of refurbished products when producers do refurbishing in-house and refurbishing outsourcing is shown in Figure 5.

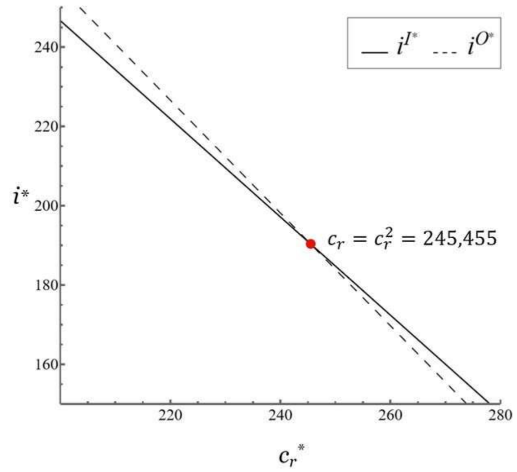

Figure 3. Variations of i^{I^*} and i^{O^*}

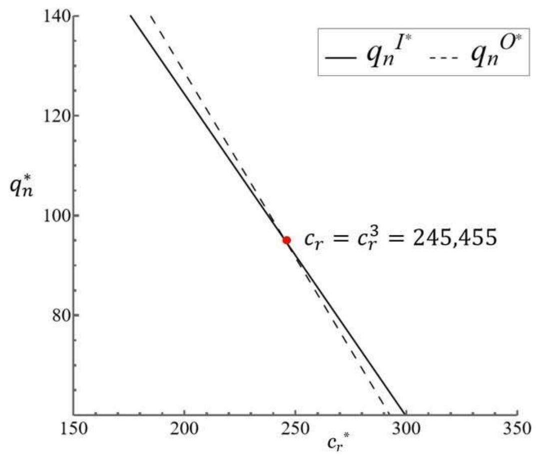

Figure 4. Variations of $q_n^{I^*}$ and $q_n^{O^*}$

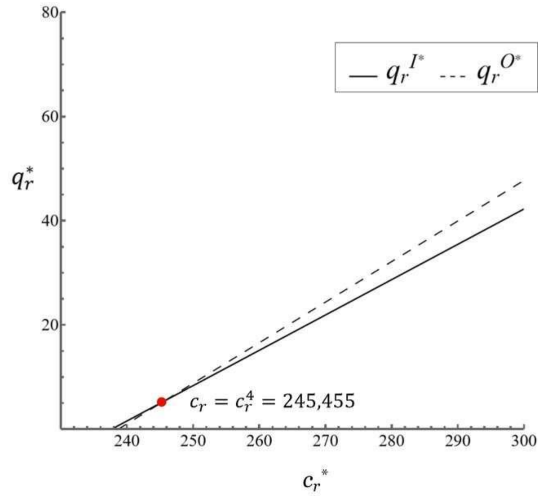

Figure 5. Variations of $q_r^{I^*}$ and $q_r^{O^*}$

Referring to the Proposition 5, it is concluded that $P_I^* > P_O^*$ with the condition $c_r > c_r^5$. Differences in producer profits are shown in Figure 6. There is an intersection point between the two graphs. The intersection point is a situation when producers get the same amount of profit, namely when $c_r = c_r^5 = 238.232$. Producers benefit more from the refurbishing in-house model than the refurbishing outsourcing model. The greater the cost of producing a refurbished product, the less profit the producer gets in both models.

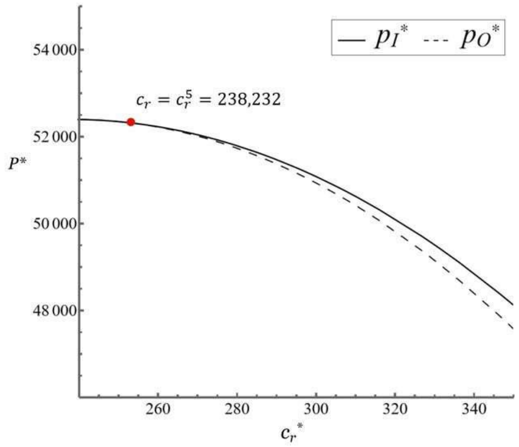

Figure 6. Variations of P_I^* and P_O^*

The proposition 6 shows that $P_I^* > P_G^*$ with the condition $c_r > c_r^6$. Even though in the refurbishing outsourcing model the industry benefits from the profits of producers and third parties, the industry in the refurbishing in-house model is still more profitable. The greater the cost of producing a refurbished product (c_r), the greater the profit. The difference in industry profits between the two models is not much different. There is a value similarity between industry profits and product production costs refurbished $c_r = c_r^6 = 148.345$. The difference in industry profits is shown in Figure 7.

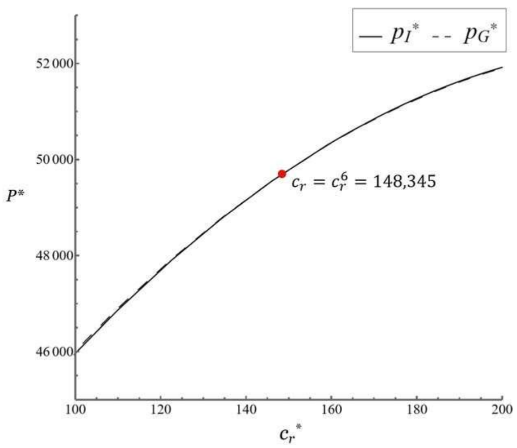

Figure 7. Variations of P_I* and P_G*

As in Proposition 7, it is proven that $E_O^* < E_I^*$ with the condition that the cost of producing the product refurbished is $c_r > c_r^6$. This shows that the refurbishing outsourcing model is more environmentally friendly than the refurbishing in-house model. Figure 8 shows that the greater the cost of producing a refurbished product, the smaller the impact on the environment.

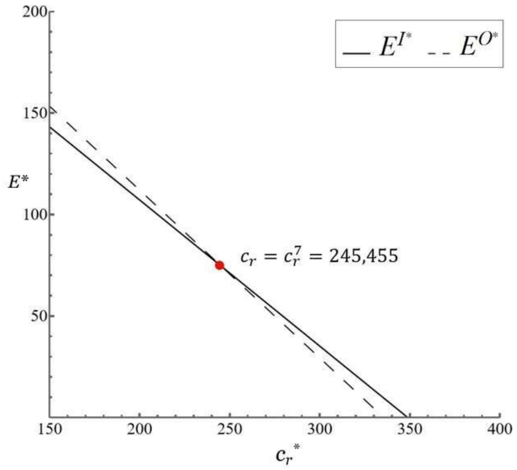

Figure 8. Variations of E^{I*} and E^{O*}

D. CONCLUSION AND SUGGESTIONS

In today's production processes of several sectors, including automotive components, electronics, furniture, and electrical appliances, commonly employ interchangeable design. This design approach offers benefits for both the assembly of new products and the disassembly for refurbishment, even though the sales of the restored goods may compete with those of the new items. As a result, the interchangeable design that needs to be renovated frequently must strike a balance between revenue from cost drivers and the effects of renovation cannibalization.

Manufacturers benefit more from the refurbishing in-house model compared to the refurbishing outsourcing model. This disparity is primarily influenced by the cost of producing a refurbished product, which directly impacts the manufacturer's profit in both models. In both scenarios, as the cost of producing a refurbished product increases, the manufacturer's profit decreases. This trend highlights the cost sensitivity within the refurbishing industry, where minimizing production costs is crucial for maximizing profits. Moreover, it's worth noting that the refurbishing outsourcing model tends to be more environmentally friendly than the refurbishing in-house model. This inverse relationship underscores the potential sustainability benefits of outsourcing refurbishing tasks to specialized facilities, which may have more efficient and eco-friendly processes. Judging from the optimum production results, producers who do refurbishing in-house choose a higher degree of interchangeability and produce more new products.

Future research in this field should focus on optimizing interchangeable design strategies by considering the trade-offs between refurbishment efficiency and cannibalization of new product sales. Additionally, a deeper analysis of cost drivers, including both direct and indirect costs, is essential for devising effective refurbishment models. Sustainability should remain a central theme, with investigations into the environmental impacts of in-house versus outsourced refurbishment and the integration of emerging technologies to enhance efficiency. Market dynamics and consumer behavior studies are needed to understand the demand for refurbished products and their effects on new product sales. Supply chain optimization and government regulations should also be explored to support sustainable refurbishment practices. Furthermore, compiling case studies and best practices can provide valuable insights for industries aiming to implement interchangeable design and refurbishment strategies. Lastly, researchers should explore how circular economy concepts can be integrated into refurbishment processes to minimize waste and resource consumption, contributing to more sustainable manufacturing practices across various sectors.

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