Marketing Refurbished Products with Carbon-Emission-Constraint Policy and Consumer Behavior: Offline vs. Online Channels

Nughthoh Arfawi Kurdhi[1], Yahya Putra Pradana[2], Yogi Pasca Pratama[3], and Vika Yugi Kurniawan[4]

***Abstract*—Refurbished products, which are repaired or restored to a like-new condition, offer a more sustainable alternative to new products by extending their lifecycle. However, the marketing of refurbished products faces several chal-lenges, including consumer perception, trust, and the impact of carbon-emission-constraint policies. This study aims to address these challenges and provide recommendations for effective marketing strategies. We explore the marketing of refurbished products within the context of carbon-emission-constraint policies, specifically comparing offline and online channels. We present two channel models, with the first model, referred to as Model O, fo-cusing on marketing refurbished products through the manufacturer's own e-commerce channel. The second model, known as Model T, explores the al-ternative approach of outsourcing the marketing activity to a third-party en-tity. Carbon-emission-constraint policies impose restrictions on businesses' carbon footprint, affecting their marketing strategies. Businesses must navi-gate these policies while effectively promoting refurbished products to envi-ronmentally conscious consumers. By addressing the challenges faced in marketing refurbished products with carbon-emission-constraint policies, consumer behavior, and comparing offline and online channels, this thesis aims to provide valuable insights for businesses and policymakers to effec-tively promote sustainable consumption and contribute to a more environ-mentally conscious industry.**

***Index Terms*—Circular Economy, Refurbishing, Distribution Channel, Carbon Emission, Consumer Behavior.**

I. Introduction

THE manufacturing sector has experienced substantial waste generation and the consequent negative environmental impacts resulting from the linear life cycle ap-proach applied to new products. In response to concerns over resource scarcity and environmental harm in the industry has led to a notable shift towards implementing a circular economy model ([1], [2]). Remanufacturing/refurbishing offers a practical solution by repairing and transforming used products into like-new items, effectively transitioning from a linear to a circular product life cycle ([3], [4]). According to ([5]), this practice has gained significant traction within the manufacturing industry as a key component of the circular economy, as it plays a crucial role in reducing waste disposal, curbing the consumption of natural resources, and minimizing material accumulation in landfills.

Engaging in refurbishing proves a highly profitable strategy for companies, as it not only conserves the raw material content but also retains much of the value added during the processes required to manufacture new products ([6], [7]). In terms of cost savings, refurbishing can lead to a reduction of 40-65 percent in manufacturing costs for the company ([8]). As a result, an increasing number of manufacturers, including Apple, Samsung, Lenovo, Fuji, Xerox, Kodak, IBM, HP, Bosch, Boeing, and Caterpillar, have incorporated refurbishing as an integral part of their business models ([9]). Moreover, refurbishing offers significant environmental benefits. It eliminates the disposal impact of returned cores and consumes fewer natural resources and less energy compared to manufacturing new products. In fact, refurbishing a product requires only about 15 percent of the energy used to make the product from scratch ([10]). Consequently, governments and environmental groups spare no effort to encourage firms to engage in refurbishing. For instance, the Waste Electrical and Electronic Equipment (WEEE) directive in the European Union promotes "extended producer responsibility," making it mandatory for all original equipment manufacturers to take responsibility for treating and recycling their products when they are no longer desired by their owners.

In recent years, global concern for environmental sustainability has led to the implementation of various policies aimed at reducing carbon emissions. A growing number of nations recognize the crucial significance of reducing carbon emissions in the pursuit of sustainable development. Consequently, carbon emission reduction and the optimization of energy structures have been integrated into the development plans of these countries. Governments have implemented a range of policies to curb emissions, including carbon taxes, carbon subsidies, carbon quotas, and carbon trading, with the aim of influencing emission behaviors ([11], [12], [13]). The implementation of carbon emission capacity regulation has proven to be a more enforceable and efficient approach to reducing carbon emissions ([14], [15], [16]). In November 2015, Jiangsu Province in China introduced carbon emission capacity regulation as a means to achieve its emission reduction objectives ([17]). This regulation involves the government setting a specific carbon emission cap. Companies are required to ensure that their carbon emissions remain below this limit; failure to do so results in financial penalties.

[1,2,4]Department of Mathematics, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Indonesia e-mail: arfa@mipa.uns.ac.id

[1]University Researcher, Industrial Engineering and Innovation Sciences, Eindhoven Univer-sity of Technology, The Netherlands

[3]Department of Development Economics, Faculty of Economics and Business, Universitas Sebelas Maret, Indonesia

[3]Ph.D Program in Asia-Pacific Regional Studies, National Dong Hwa University

Manuscript received July 18, 2023; accepted September 14, 2023.

Through the implementation of the carbon emission capacity regulation, manufacturers are obligated to make adjustments to the quantity of both new and remanufactured products, consequently mitigating the environmental impact associated with production activities.

To the best of our understanding, there is limited existing literature that explores the economic and environmental advantages associated with various channel structures for marketing refurbished products. However, marketing refurbished products gives rise to several inquiries concerning the decision-making process for distribution channels. The rapid growth of e-commerce and the increasing demand for sustainable products have created a unique opportunity for businesses to market refurbished products ([18], [19], [20]). The manufacturer typically sells refurbished products through various channels, including their own e-commerce websites and online auction platforms like eBay, as well as authorized distributors. For example, all refurbished Apple computers and notebooks, after being collected from customers and undergoing the replacement of any defective modules identified during testing, are sold through Apple's online store. Canon also operates websites dedicated to a wide range of refurbished products, including EOS Digital SLR Cameras, PowerShot Digital Cameras, PIXMA Printers, and VIXIA Camcorders. In another approach, the manufacturer sells refurbished products through authorized third parties. For instance, Panasonic partners with three authorized service center partners, namely Telrepco, Buy Tough, and Rugged Depot, to sell their refurbished Toughbook computers.

Researchers have acknowledged the distinction in consumers' perception regarding the quality of new and refurbished products ([21]). As a result, consumer behavior towards these products assumes a crucial role in the pricing issue, as it can impact the demand for both product types ([22], [23], [24]). According to the research conducted by ([25]) and ([9]), the availability of refurbished products at discounted prices raises concerns about potential sales cannibalization for higher-margin new products. Consequently, many companies decide against offering refurbished products alongside new ones. However, by incorporating both refurbished and new products into their product lineup, firms can effectively target different customer segments and capture sales from "low-end" customers who prefer refurbished options. Despite the possibility of cannibalizing some sales of new products, the overall financial benefit to the company can be significant when carefully determining the pricing and quantity of refurbished products. There are two distinct customer segments in the market: high-end and low-end. High-end customers are open to purchasing new products but may also consider refurbished alternatives. In contrast, low-end customers exclusively prefer refurbished products. However, the 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.

In this paper, we introduce two innovative channel models tailored for manufacturers who distribute new units through independent retailers. Our primary objective is to offer comprehensive solutions to address the intricacies of marketing refurbished products, taking into account the evolving landscape shaped by contemporary industry practices. The first model, known as Model O, centers on the strategic marketing of refurbished products via the manufacturer's dedicated e-commerce channel. This approach capitalizes on the manufacturer's direct engagement with customers through their online platform, presenting a unique opportunity to influence purchasing decisions and behavior. The second model, referred to as Model T, delves into an alternative avenue—outsourcing the marketing activities to a third-party entity. By exploring this path, we aim to provide manufacturers with a fresh perspective on how to navigate the refurbished product market, utilizing external expertise to amplify their reach and impact. Our models are not constructed in isolation; rather, they emerge from a synthesis of empirical observations and industry insights. What sets our research apart is its pioneering focus on the intersection of carbon emission policies and consumer behavior within these channel models. With the growing global concern for environmental sustainability, carbon emission policies have emerged as a pivotal factor influencing corporate strategies. We investigate how these policies interplay with the marketing of refurbished products. Moreover, we explore the dynamic dimension of consumer behavior—how choices and preferences are shaped by environmental considerations, cost factors, and product quality. Our paper endeavors to shed light on this multifaceted landscape, providing manufacturers with a robust framework to optimize their marketing strategies for refurbished products in the context of evolving environmental regulations and consumer sentiments. By doing so, we aim to not only enhance businesses' profitability but also contribute to a more sustainable and eco-conscious industry.

II. Model Assumptions

We are considering a manufacturer that sells new products while exploring two op-tions for marketing refurbished products. Specifically, we are examining two distri-bution channel designs: Model O and Model T (refer to Fig. 1). In Model O, the manufacturer directly sells refurbished products through its own e-channel. In Model T, the manufacturer outsources the marketing activity to a third-party entity.

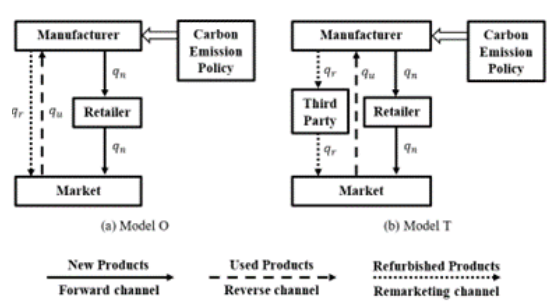


Fig. 1: Two distribution channel models

There are two market segments: high-end and low-end. Customers who shop at higher price points are more likely to buy new products, whereas those who shop at lower costs only buy refurbished goods. The desire for new items, or high-end demand, is Q in the absence of refurbished products. If the market for refurbished goods is there, a number of high-end customers, $\alpha(p_r)$, will migrate to them, if they are available. A retailer captures $a-lp_r$ low-end buyers who won't buy new items by promoting a refurbished product for p_r, where a is the potential market of refurbished products and l is the price sensitivity. The following are the numbers of customers who buy new and refurbished products:

$$q_n = Q - \alpha(p_r), \tag{1}$$
$$q_r = a - lp_r + \alpha(p_r). \tag{2}$$

where q_n and q_r are the production quantity of new and refurbished products. We assume that cannibalization mimics a general linear switching function, that is

$$\alpha(p_r) = b(p_n - p_r), \tag{3}$$

for some coefficient cannibalization b, where p_n is the new product price. We consider our model with unconstrained refurbished product supply throughout the product life cycle. The volume of used products that could be collected is huge, and this study assumes there is no upper limit for the total available refurbishing quantity.

III. Model Development and Optimal Solution

In this section, we consider two distribution channel formats: Model O and Model T, in which Π^i_j represents the profit for player j under supply chain model i. Superscript $j \in \{O,T\}$ denotes Model O and Model T, while subscript $i \in \{O,R,T,J\}$ denotes the manufacturer, the retailer, third party, and the total supply chain, respectively.

Model Online Channel (Model O)

In Model O, since the manufacturer sells refurbished products directly through an e-channel, the manufacturer's problem is as follows:

$$\max_{w_n^O, p_r^O} \quad \Pi_O^O = (w_n^O - c_n)q_n^O + (p_r^O - c_r)q_r^O$$
$$\text{s.t.} \quad e_n q_n^O + e_r q_r^O \le K$$

where w_n^O is the wholesale price; c_n and c_r are the base unit production costs of new and refurbished products; whereas e_n, e_r, and K are carbon emissions per unit of new and refurbished products, and carbon emission capacity, respectively.

Given the wholesale price w_n^O and the retail price p_r^O, the retailer's problem is:

$$\max_{p_n^O} \quad \Pi_R^O = (p_n^O - w_n^O - c_R)q_n^O,$$

where c_R is the unit cost of selling a new product via retailer. We solve the problems by using Karush–Kuhn–Tucker (KKT) conditions and backward induction to determine the subgame perfect equilibrium. Once the manufacturer's maximization problem is solved with respect to w_n^O and p_r^O, the retailer can maximize its profit by choosing p_n^{O*}. The following proposition summarizes both parties' optimal decisions.

Proposition 1. Let $A = 2be_n^2 - 4be_ne_r + 2(b+2l)e_r^2$, $I_1 = a+q-lc_r$, and $I_2 = ab+(b+l)q-bl(c_n+c_R)$. The value $\lambda = 0$ (partial carbon capacity) happens when just a portion of the carbon capacity is used, while $\lambda > 0$ (full carbon capacity) occurs when all of the carbon capacity is implemented, resulting in two pairs of optimal solutions in Model O. Therefore, the equilibrium quantities, product prices, wholesale prices, and profits can be summarized as follows:

$$q_n^{O*} = \frac{1}{4}(q - b(c_n - c_r + c_R))$$
$$q_r^{O*} = \frac{1}{4}(q + 2a + b(c_n + c_R) - (b+2l)c_r)$$
$$p_n^{O*} = \frac{(2ab + q(2b+3l) + bl(c_n + c_r + c_R))}{4bl}$$
$$p_r^{O*} = \frac{(a+q+lc_r)}{2l}$$
$$w_n^{O*} = \frac{(ab + q(b+l) + bl(c_n - c_R))}{2bl}$$
$$\Pi_O^{O*} = \frac{1}{8bl}\Big[2a^2b + 4abq + (2b+l)q^2 + bl\Big(bc_n^2 + (b+2l)c_r^2 - 2c_n(q + b(c_r - c_R)) + c_R(bc_R - 2q) - 2c_r(q + 2a + bc_R)\Big)\Big]$$
$$\Pi_R^{O*} = \frac{(q - b(c_n - c_r + c_R))^2}{16b}$$

for $\lambda = 0$ and

$$q_n^{O*} = \frac{2bKe_n - b(2K + I_1e_n)e_r + I_2e_r^2}{A}$$
$$q_r^{O*} = \frac{be_n(I_1e_n - 2K) + (2K(b+2l) - I_2e_n)e_r}{A}$$
$$p_n^{O*} = \frac{1}{blA}\Bigg[be_n\Big((b(I_1 + 2lc_r) + 2lq)e_n - 2Kl\Big) - be_r\Big((a(2b-l) + (b+l)(2q + lc_r) + bl(c_n + c_R))e_n + 2Kl\Big) + \Big((b+3l)(ab + q(b+l)) + bl(b+l)(c_n + c_R)\Big)e_r^2\Bigg]$$
$$p_r^{O*} = \frac{1}{lA}\Bigg[b(I_1 + 2lc_r)e_n^2 - \Big(4Kl + (2ab + (2b-l)q + bl(c_n + c_r + c_R))e_n\Big)e_r + \Big(a(b+4l) + q(b+3l) + bl(c_n + c_R)\Big)e_r^2\Bigg]$$
$$\Pi_O^{O*} = \frac{1}{2blA}\Bigg[-8bK^2l + be_n\Big(4Kl(q - b(c_n - c_r + c_R)) + bI_1^2e_n\Big) + 2b\Big(2Kl(2a + q + bc_n - (b+2l)c_r + bc_R) - I_1I_2e_n\Big)e_r + I_2^2e_r^2\Bigg]$$
$$\Pi_R^{O*} = \frac{(2bKe_n - b(2K + I_1e_n)e_r + I_2e_r^2)^2}{bA^2}$$

for $\lambda > 0$.

A. Model Offline Channel (Model T)

Model T, since the manufacturer sells refurbished products directly through a third party, the manufacturer's problem is as follows:

$$\begin{aligned} \max_{(w_n^T, w_r^T)} \quad & \Pi_o^T = (w_n^T - c_n)q_n^T + (w_r^T - c_r)q_r^T \\ \text{s.t.} \quad & e_n q_n^T + e_r q_r^T \leq K \end{aligned}$$

Given the wholesale prices w_n^T and w_r^T, the retailer's problem is:

$$\max_{(p_n^T)} \quad \Pi_R^T = (p_n^T - w_n^T - c_R)q_n^T$$

Given the wholesale prices w_n^T and w_r^T and the new product price p_n^T, the third party problem is:

$$\max_{(p_r^T)} \quad \Pi_T^T = (p_r^T - w_r^T - c_T)q_r^T$$

We solve the problems using the Karush–Kuhn–Tucker (KKT) conditions and backward induction to determine the subgame perfect equilibrium. Once the manufacturer's maximization problem is solved with respect to w_n^T and p_r^T, the retailer and the third party can maximize their profits by choosing $p_n^{T^*}$ and $p_r^{T^*}$, respectively. The following proposition summarizes both parties' optimal decisions.

Proposition 2. Let

$$B = 2b(b+2l)^2 e_n^2 - 4b(b+l)(b+2l)e_n e_r + 2(b+4l)(b+l)^2 e_r^2.$$

The value $\lambda = 0$ (partial carbon capacity) occurs when only a portion of the carbon capacity is used, while $\lambda > 0$ (full carbon capacity) occurs when all the carbon capacity is implemented, resulting in two pairs of optimal solutions in Model T. Therefore, the equilibrium quantities, product prices, wholesale prices, and profits can be summarized as follows:

$$\begin{aligned}
q_n^{T*} &= \frac{ab + 2q(b+l) + b\left((b+l)(c_r + c_T) - (b+2l)(c_n + c_R)\right)}{8(b+l)} \\
q_r^{T*} &= \frac{a(3b+4l) + 2q(b+l) + b(b+2l)(c_n + c_R) - (b+l)(b+4l)(c_r + c_T)}{8(b+2l)} \\
p_n^{T*} &= \frac{1}{4bl(b+2l)} [ab(2b+5l) + 2q(b+l)(b+3l) \\
&\quad + bl\left((b+2l)(c_n + c_R) + (b+l)(c_r + c_T)\right)] \\
p_r^{T*} &= \frac{1}{8l(b+l)(b+2l)} \Big[a(4b^2 + 15bl + 12l^2) + 2q(b+l)(2b+5l) \\
&\quad + l\left(b(b+2l)c_n + (b+l)(3b+4l)c_r + b(b+2l)c_R + (b+l)(3b+4l)c_T\right] \\
w_n^{T*} &= \frac{ab + q(b+l) + bl(c_n - c_R)}{2bl} \\
w_r^{T*} &= \frac{a + q + l(c_r - c_T)}{2l} \\
\Pi_O^{T*} &= \frac{1}{16bl(b+l)(b+2l)} \Big[a^2 b(4b^2 + 9bl + 4l^2) + 4abq(b+l)(2b+3l) \\
&\quad + bl \Big(b(b+2l)^2 c_n^2 + (b+4l)(b+l)^2 (c_r^2 + c_T^2) \\
&\quad + (b+2l)\left(b(b+2l)c_R - 4q(b+l) - 2ab\right) c_R \\
&\quad - 2(b+l)\left(a(3b+4l) + 2q(b+l) + b(b+2l)c_R\right) c_T \\
&\quad - 2(b+2l)\left(ab + (b+l)(2q + b(c_r + c_T)) - b(b+2l)c_R\right) \\
&\quad + 2(b+l)\left((b+l)((b+4l)c_T - 2q) - a(3b+4l) - b(b+2l)c_R\right) c_r \\
&\quad + 4(b+l)^3 q^2] \\
\Pi_R^{T*} &= \frac{\left(ab + 2q(b+l) + b\left((b+l)(c_r + c_T) - (b+2l)(c_n + c_R)\right)\right)^2}{32b(b+l)(b+2l)} \\
\Pi_T^{T*} &= \frac{1}{64(b+l)(b+2l)^2} [(a(3b+4l) + 2q(b+l) + b(b+2l)(c_n + c_R) \\
&\quad - (b+l)(b+4l)(c_r + c_T)]^2
\end{aligned}$$

for $\lambda = 0$ and

$$\begin{aligned}
q_n^{T*} &= \frac{1}{B} [(b+2l)\left((b+l)(I_2 e_r - 2bK)e_r\right. \\
&\quad + b\left(2K(b+2l) + (b+l)(lc_T - I_1)e_r\right) e_n)] \\
q_r^{T*} &= \frac{1}{B} [(b+l)\left(2K(b+l)(b+4l)e_r\right. \\
&\quad - b(b+2l)(lc_T - I_1)e_n^2 - (b+2l)(2bK + I_2 e_r)e_n)] \\
p_n^{T*} &= \frac{1}{blB} [b(b+2l)\left(ab(b+3l) + (b+l)(b+4l)q\right. \\
&\quad + bl(b+l)(c_r + c_T)e_n^2 + (b+l)^2 \left((b+6l)(ab + q(b+l))\right) \\
&\quad + bl(b+2l)(c_n + c_R)e_r - 4bKl)] \\
&\quad - b(b+l)(b+2l)\left(4Kl + (a(2b-l) + 2q(b+l)\right. \\
&\quad + l\left(b(c_n + c_R) + (b+l)(c_r + c_T)\right) e_r)) e_n] \\
p_r^{T*} &= \frac{1}{lB} \Big[b(b+2l)\left((b+3l)(a+q) + l(b+l)(c_r + c_T)\right) e_n^2 \\
&\quad + (b+l) \big(a(b^2 + 8bl + 8l^2) + (b+l)(b+6l)q \\
&\quad + bl(b+2l)(c_n + c_R)e_r - 2Kl(3b+4l)) e_r] \\
&\quad - (b+2l)\left(2bKl + (b+l)\left(2ab + q(2b-l)\right.\right. \\
&\quad + bl(c_n + c_r + c_R + c_T)) e_r) e_n] \\
w_n^{T*} &= \frac{1}{blB} [b(b+2l)\left(ab(b+3l) + (b+l)(b+4l)q\right. \\
&\quad + bl\left((b+l)(c_r + c_T) - 2(b+2l)c_R\right) e_n^2] \\
&\quad + (b+l)^2 (b+4l)(I_2 + 2blc_n)e_r^2 - b(b+l)\left(8Kl(b+2l)\right. \\
&\quad + \big(a(2b^2 + bl - 4l^2) + 2(b+l)^2 q \\
&\quad + l\left(b(b+2l)(c_n - 3c_R) + (b+l)(b+4l)(c_r + c_T)\right)) e_r) e_n] \\
w_r^{T*} &= \frac{1}{lB} \Big[b(b+2l)^2 \left(I_1 + l(2c_r - c_T)\right) e_n^2 \\
&\quad - (b+2l)\left(ab(2b+l) + 2(b-l)(b+l)q\right. \\
&\quad + bl\left((b+2l)(c_n + c_R) + (b+l)(c_r - 3c_T)\right) e_n e_r] \\
&\quad - (b+l) \big(8Kl(b+2l) - \big(a(b^2 + 8bl + 8l^2) \\
&\quad + (b+l)(b+6l)q + l\left(b(b+2l)(c_n + c_R)\right. \\
&\quad - 2l(b+l)(b+4l)c_T)) e_r) e_r] \\
\Pi_O^{T*} &= \frac{1}{2blB} \Big[b^2 (b+l)(b+2l)(I_1 - lc_T)^2 e_n^2 \\
&\quad - 2b(b+2l)\left(-2Kl\left(ab + 2(b+l)q + b\left((b+l)(c_r + c_T)\right.\right.\right. \\
&\quad - (b+2l)(c_n + c_R) + (b+l)(I_1 + lc_T)I_2 e_r e_n) \\
&\quad + (b+l) \big(-16bK^2 l(b+2l) + 4bKl\left(a(3b+4l) + 2(b+l)q\right. \\
&\quad + b(b+2l)(c_n + c_R) - (b+l)(b+4l)(c_r + c_T))) + (b+2l)I_2^2 e_r^2] \\
\Pi_R^{T*} &= \frac{2(b+l)(b+2l)}{bB^2} [(b+l)(2bK - I_2 e_r)e_r + \\
&\quad \left(-2bK(b+2l) + b(b+l)(I_1 + lc_T)e_r\right)e_n]^2 \\
\Pi_T^{T*} &= \frac{(b+l)}{B^2} \Big[b(b+2l)(lc_T - I_1)e_n^2 - 2K(b+l)(b+4l)e_r \\
&\quad + (b+2l)(2bK + I_2 e_r)e_n]^2
\end{aligned}$$

for $\lambda > 0$

IV. Model Analysis

In this part, we look at the differences between the two models. To allow comparison of the interior point solutions to both the models, the condition of $0 < q_r < q_n$ is imposed and the following assumption is derived. **Assumption 1.** Let $D = bI_1 e_n - I_2 e_r$, $K_1 = \frac{De_n}{2be_n - 2(b+2l)e_r}$, and $K_2 = \frac{D(e_n + e_r)}{4be_n - 4(b+l)e_r}$. In both the models, the value of carbon capacity is not too small or too large; that is, $K_1 < K < K_2$.

Subsequently, the best possibilities for the models given were examined in their various forms. Only when $\lambda > 0$ (full carbon capacity) will the analyses' optimal solution be used. **Proposition 3.** The manufacturer is more likely to set a higher wholesale price of new products in Model O than in Model T, that is $w_n^{(O^*)} > w_n^{(T^*)}$ for any $K \in (K_1, K_2)$. **Proof.** To prove $w_n^{(O^*)} > w_n^{(T^*)}$, we must show that:

$$\begin{aligned} w_n^{(O^*)} - w_n^{(T^*)} = \frac{2}{AB}\Bigg[& (-b^2(b+2l)(I_1+(b+l)c_T)e_n^3 \\ & + (b+l)(4K(b^2+3bl+4l^2) \\ & + (-bI_2+(b+l)(b+2l)(b+4l)c_T)e_r)e_r^2 \\ & + b(4bK(b+2l) \\ & + (a(b+l)(b+4l)+(b^2+6bl+6l^2)q \\ & - l(b(b+2l)(c_n+c_R) \\ & + l(3b+4l)c_r) \\ & + (b+l)(3b^2+9bl+4l^2)c_T)e_r)e_n^2 \\ & + (-8bK(b+l)(b+2l) \\ & + ab(b^2-2bl-4l^2) \\ & + (b-4l)(b+l)^2 q \\ & + bl(l(3b+4l)c_n - b(b+l)c_r \\ & + l(3b+4l)c_R) \\ & - b(b+l)(3b^2+14bl+12l^2)c_T)e_r\Bigg] e_n > 0. \end{aligned}$$

This is true for any $K \in (K_1, K_2)$. That is to say, $w_n^{(O^*)} > w_n^{(T^*)}$ always holds for any $K \in (K_1, K_2)$.

Based on Proposition 3, wholesale prices for new products are higher when refur-bished products are sold directly by the manufacturer through e-channels. This is inseparable from the competition between manufacturer and retailer to attract con-sumers. Therefore, this moment is used by manufacturer to sell new products to retailer at higher prices so that the refurbished products they sell through e-channels can compete in the market in terms of price.

Proposition 4. Let $E = 2b(b+2l)e_n^2 - 2l(3b+4l)e_ne_r - 2b(b+l)e_r^2$ and

$$\begin{aligned} K_3 = \frac{1}{E}\Bigg[& b(b+2l)(I_1+(b+l)c_T)e_n^3 \\ & - (b+2l)(I_2+2b(b+l)c_T)e_n^2e_r \\ & + (b+l)(bI_1+(b+2l)^2c_T)e_ne_r^2 \\ & - (b+l)I_2e_r^3 \Bigg] \end{aligned}$$

When compared to Model O,

- if $e_n > (1+l/b)e_r$, the manufacturer determine greater or equal price of new products in Model T ($p_n^{(O^*)} \leq p_n^{(T^*)}$) whenever $K \in (K_1, K_3]$, otherwise $p_n^{(O^*)} > p_n^{(T^*)}$ whenever $K \in (K_3, K_2)$,
- if $e_n = (1+l/b)e_r$, the price of new product in both models are equal for any $K \in (K_1, K_2)$, and
- if $e_n < (1+l/b)e_r$, the result is the opposite with (1).

Proof. Note that:

$$\begin{aligned} p_n^{(O^*)} - p_n^{(T^*)} = -\frac{2}{AB}\Bigg[& (be_n-(b+l)e_r) \\ & \times \Big(b(b+2l)(I_1+(b+l)c_T)e_n^3 + (b+l)(2bK - I_2e_r)e_r^2 \\ & - (b+2l)(2bK+(I_2+2b(b+l)c_T)e_r)e_n^2 \\ & + (2Kl(3b+4l)+(b+l)(bI_1+(b+2l)^2c_T)e_r)e_ne_r\Bigg] = 0 \\ \Leftrightarrow K = K_3. \end{aligned}$$

Based on the value of e_n, there are three cases for this analysis:

- if $e_n > (1+l/b)e_r$, there are two cases for this analysis because $K_3 \in (K_1, K_2)$. The value of $p_n^{(O^*)} - p_n^{(T^*)}$ is non-positive for any $K \in (K_1, K_3]$. Second case, for any $K \in (K_3, K_2)$, the value of $p_n^{(O^*)} - p_n^{(T^*)}$ is positive. That is to say, $p_n^{(O^*)} \leq p_n^{(T^*)}$ always holds for any $K \in (K_1, K_3]$ and $p_n^{(O^*)} > p_n^{(T^*)}$ always holds for any $K \in (K_3, K_2)$,
- if $e_n = (1+l/b)e_r$, $p_n^{(O^*)} - p_n^{(T^*)} = 0$ or $p_n^{(O^*)} = p_n^{(T^*)}$ for any $K \in (K_1, K_2)$, and
- if $e_n < (1+l/b)e_r$, the result is the opposite with (1).

Under Proposition 4, retailer sell new products at lower prices in Model O when emission capacity is limited but the environmental impact of new products is large. Under these conditions, the products that can be produced and sold are limited. Therefore, retailer can take little risk (earn less profit) to compete with manufacturer by offering products to consumers at low prices. However, if the manufacturer has more freedom to produce due to the large carbon capacity that can be used, the re-tailer prefers to set a higher selling price in Model O to cover the cost of purchasing the new product from the manufacturer and the cost of selling the product to con-sumers, or a lower price in Model T so that the price offered can compete with third-party.

Proposition 5. When compared to the manufacturer in Model O, the third-party determine greater or equal selling price of refurbished products in Model T ($p_r^{(O^*)} \leq p_r^{(T^*)}$) whenever $K \in (K_1, K_3]$, otherwise $p_r^{(O^*)} > p_r^{(T^*)}$ whenever $K \in (K_3, K_2)$.

Proof. Note that:

$$\begin{aligned} p_r^{(O^*)} - p_r^{(T^*)} = -\frac{2}{AB}\Bigg[& b(e_n-e_r)\Big(b(b+2l)(I_1+(b+l)c_T)e_n^3 \\ & + (b+l)(2bK - I_2e_r)e_r^2 \\ & - (b+2l)(2bK+(I_2+2b(b+l)c_T)e_r)e_n^2 \\ & + (2Kl(3b+4l)+(b+l)(bI_1+(b+2l)^2c_T)e_r)e_ne_r\Big)\Bigg] \\ = 0 & \\ \Leftrightarrow K = K_3. & \end{aligned}$$

There are two cases for this analysis because $K_3 \in (K_1, K_2)$. The value of $p_r^{(O^*)} - p_r^{(T^*)}$ is non-positive for any $K \in (K_1, K_3]$. Second case, for any $K \in (K_3, K_2)$, the value of $p_r^{(O^*)} - p_r^{(T^*)}$ is positive. That is to say, $p_r^{(O^*)} \leq p_r^{(T^*)}$ always holds for any $K \in (K_1, K_3]$ and $p_r^{(O^*)} > p_r^{(T^*)}$ always holds for any $K \in (K_3, K_2)$.

Based on Proposition 5, in the O model, when the emission capacity is very limited, the manufacturer will sell the refur-bished product at a lower price. This allows the manufacturer to offer a price that competes with retail prices. However, when emis-sion capacity is aligned with a larger production quantity, the manufacturer chooses to increase profits by selling refurbished products at a higher price in Model O com-pared to third-party in Model T who face price competition with retailer.

Proposition 6. The manufacturer is more likely to produce a higher or equal quantity of new products ($q_n^{(O^*)} \geq q_n^{(T^*)}$) and a lesser or equal quantity of refurbished products ($q_r^{(O^*)} \leq q_r^{(T^*)}$) in Model O than in Model T whenever $K \in (K_1, K_3]$; otherwise, $q_n^{(O^*)} < q_n^{(T^*)}$ and $q_r^{(O^*)} > q_r^{(T^*)}$ whenever $K \in (K_3, K_2)$.

Proof. Note that:

$$q_n^{(O^*)} - q_n^{(T^*)} = -\frac{2}{AB}\Big[bl\Big(b(b+2l)(I_1+(b+l)c_T)e_n^3$$

$$
\begin{aligned}
&+(b+l)(2bK-I_2e_r)e_r^2\\
&-(b+2l)(2bK+(I_2+2b(b+l)c_T)e_r)e_n^2\\
&+(2Kl(3b+4l)+(b+l)(bI_1+(b+2l)^2c_T)e_r)e_ne_r\Big)e_r\Big]\\
&=0\\
&\Leftrightarrow K=K_3,
\end{aligned}
$$

and

$$
\begin{aligned}
q_r^{(O^*)}-q_r^{(T^*)}=\frac{2}{AB}\Big[bl\Big(&b(b+2l)(I_1+(b+l)c_T)e_n^3\\
&+(b+l)(2bK-I_2e_r)e_r^2\\
&-(b+2l)(2bK+(I_2+2b(b+l)c_T)e_r)e_n^2\\
&+(2Kl(3b+4l)+(b+l)(bI_1+(b+2l)^2c_T)e_r)e_ne_r\Big)e_n\Big]\\
=0&\\
\Leftrightarrow K=K_3&.
\end{aligned}
$$

There are two cases for this analysis because $K_3 \in (K_1, K_2)$. The value of $q_n^{(O^*)} - q_n^{(T^*)}$ is non-negative and $q_r^{(O^*)} - q_r^{(T^*)}$ is non-positive for any $K \in (K_1, K_3]$. Second case, for any $K \in (K_3, K_2)$, the value of $q_n^{(O^*)} - q_n^{(T^*)}$ is negative and $q_r^{(O^*)} - q_r^{(T^*)}$ is positive. That is to say, $q_n^{(O^*)} \geq q_n^{(T^*)}$ and $q_r^{(O^*)} \leq q_r^{(T^*)}$ always holds for any $K \in (K_1, K_3]$ and $q_n^{(O^*)} < q_n^{(T^*)}$ and $q_r^{(O^*)} > q_r^{(T^*)}$ always holds for any $K \in (K_3, K_2)$.

As stated in Proposition 6, the manufacturer prefers to focus on producing new products in Model O and refurbished products in Model T when carbon capacity is limited. This is based on Propositions 3 and 5, which state that the price is higher in Model O for new products and in Model T for refurbished products. However, the manufacturer prefers to produce refurbished products in Model O when carbon capacity is larger because they want to maximize profits to cover production costs.

V. Numerical Solution

The implementation of the refurbishment model uses some parameter values. We evaluate our results using numerical simulations in *Mathematica* to further understand how the parameters, especially the upper limit of the carbon capacity (K), affect the optimal solutions of two different models. We choose the values of the production costs for new and refurbished products to be $c_n = 550$ and $c_r = 200$, respectively. The environmental impact per unit of the two types of products are correspondingly $e_n = 150$ and $e_r = 100$. In addition, we consider that the cost of selling new products from a retailer and refurbished products from a third party are $c_R = 20$ and $c_T = 30$, respectively. We also chose $a = 90$, $l = 0.5$, $b = 0.23$, and $q = 250$. To ensure that $0 < q_r < q_n$, the upper limit of the carbon emission capacity should be in the range $4648.31 < K < 8904.22$.

The quantity of new and refurbished products increases consistently with the addition of usable carbon capacity in both models, as shown in Fig. 2. According to Proposition 6, the new products produced by the manufacturer are greater in Model O than in Model T when $K < K_3$, but the opposite is true for refurbished products. However, when $K = K_3 = 4813.46$, the quantities of these products reach the same values of $q_n = 31.17$ and $q_r = 1.38$. The observed trend in the quantity of new and refurbished products concerning the available usable carbon capacity (K) underscores the delicate balance manufacturers must strike between environmental sustainability and product output. The increase in both new and refurbished products with higher carbon capacity reflects the potential for economic growth. Proposition 6 introduces a critical decision point—when K falls below the threshold value K_3, Model O becomes the preferred choice for new product production, yielding greater quantities than Model T. Conversely, for refurbished products, Model T proves more efficient under these conditions. However, the equilibrium reached at $K_3 = 4813.46$ signifies an optimal state where both models produce the same quantities of new and refurbished products. This equilibrium highlights the need for manufacturers to align their production strategies with environmental policies, as it demonstrates that sustainable practices can harmonize with economic output. This presents a roadmap for businesses seeking to navigate the complex terrain of environmentally conscious production while maintaining competitiveness in the marketplace.

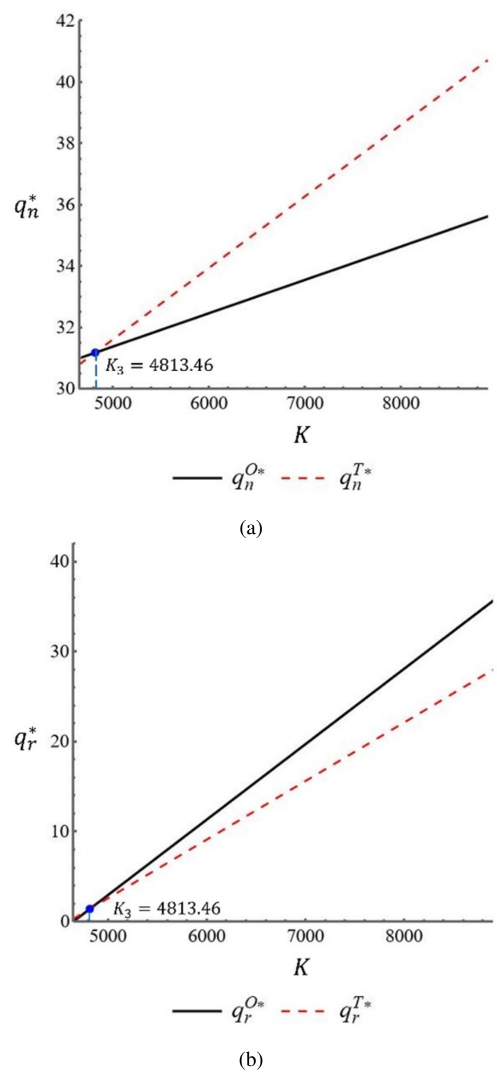


Fig. 2: Effects of K on quantity of (a) new product and (b) refurbished product.

Furthermore, Fig. 3 shows that the wholesale price for new products in both models decreases steadily as the usable carbon capacity increases. The price difference be-tween the two models also increases. The manufacturer sets a higher product price in Model O compared to Model T, which is consistent with Proposition 3. The insights from Fig. 3 regarding the wholesale price dynamics of new products offer valuable considerations for manufacturers seeking to optimize their pricing strategies. As the available usable carbon capacity (K) increases, the wholesale price for new products consistently declines in both models, reflecting a broader industry trend driven by environmental factors and market competitiveness. Of particular note is the widen-ing price disparity between the two models, where Model O consistently maintains a higher product price compared to Model T. This pricing distinction aligns with Proposition 3, underscoring the rationale behind the manufacturer's pricing strategy. This observation indicates that, as carbon capacity expands, manufacturers employ-ing Model O may leverage their environmentally friendly practices to justify a pre-mium price for new products, potentially attracting eco-conscious consumers willing to pay more for sustainable goods. Conversely, Model T may gain a competitive edge by offering a lower price point, appealing to cost-sensitive consumers. These findings illuminate the delicate interplay between environmental considerations, pricing strategies, and consumer behavior within the context of sustainable product offerings.

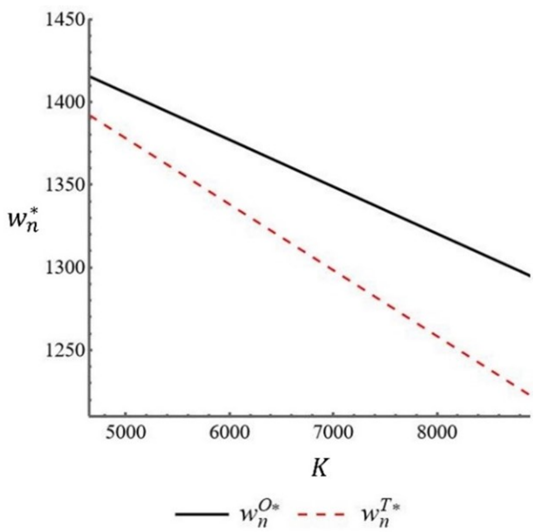


Fig. 3: Effects of K on wholesale price of new product.

Referring to Proposition 4, there are three possible outcomes. As observed in Fig. 4, the price of the new product in Model O is higher than that in Model T when $K < K_3$ because $e_n = 150 < \left(1+\frac{l}{b}\right) e_r = 317.39$. In addition, Fig. 4 also shows that the price of each product decreases as the emission capacity increases. The prices of new and refurbished products in both models reach the same value when $K = K_3 = 4813.46$, $p_n = 1566.34$ and $p_r = 614.9$, respectively. Proposition 4 yields three distinct pricing outcomes, each shedding light on the complex interplay between emission capacity, pricing, and product type. In the initial scenario, represented in Fig. 4, where usable carbon capacity (K) is less than the threshold K_3, Model O sets a higher price for new products compared to Model T. This discrepancy arises because the emissions for new products (e_n) in Model O are lower than those for refurbished products (e_r), aligning with the proposition's stipulation. Furthermore, Fig. 4 underscores a consistent trend: as emission capacity increases, the prices of both new and refurbished products decrease across both models. This trend reflects the broader influence of environmental considerations on pricing strategies. The equilibrium, a pivotal point in this analysis, emerges at $K_3 = 4813.46$, where both new and refurbished products in both models share identical prices. At this equilibrium, manufacturers can offer consumers price parity for both product types, effectively harmonizing economic viability with sustainability objectives, a critical insight for businesses navigating the eco-conscious marketplace.

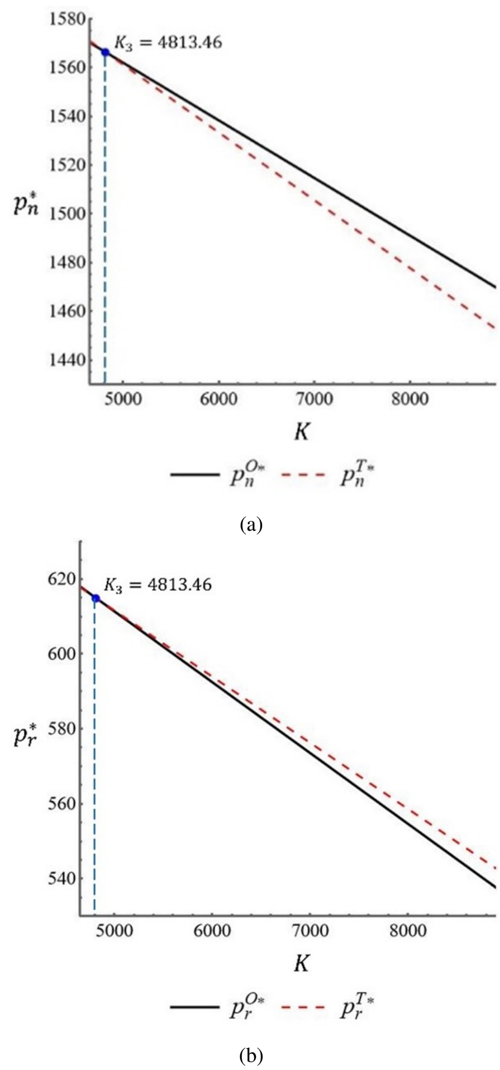


Fig. 4: Effects of K on selling price of (a) new product and (b) refurbished product.

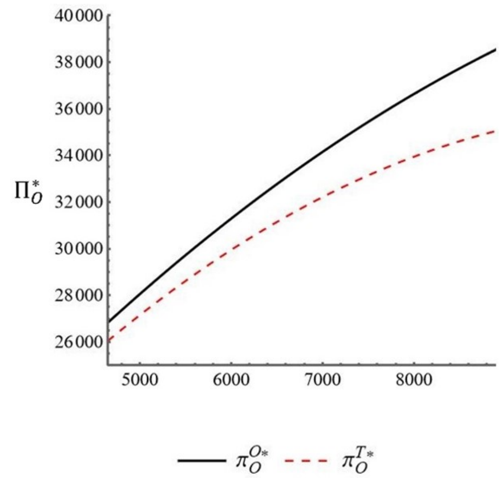
Fig. 5 illustrates that, as the carbon emission capacity increases, the profitability of all players, including both manufacturers and retailers, rises. However, an interest-ing distinction emerges: manufacturers achieve higher profits in Model O, whereas retailers see improved profitability in Model T. This finding suggests that the choice of channel model significantly impacts the distribution of profits between manufac-turers and retailers, and it underscores the importance of align-ing business strategies with carbon emission considerations. Manufacturers operating under Model O may leverage their direct e-commerce channel to capture a larger share of the profit, while retailers in Model T benefit from the outsourcing arrangement, which boosts their profitability. This insight has implications for businesses seeking to optimize their profit margins while simultaneously adhering to environmental sus-tainability objectives.

VI. Conclusion

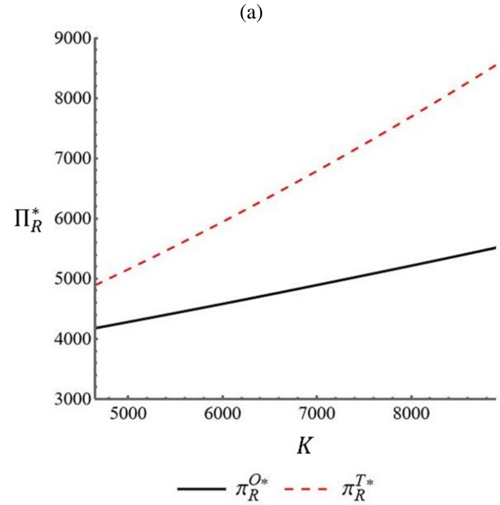
Despite manufacturers such as Apple, Canon, HP, and Panasonic adopting different supply chains for marketing remanufactured products, there is limited literature on manu-facturers' distribution channel decisions and the environmen-tal impacts. This paper examines manufacturers' distribution channel choices and their effects on environmental perfor-mance. Two channel models are presented: Model O focuses on marketing refurbished products through the manufacturer's e-commerce channel, while Model T explores outsourcing the marketing activity to a third-party. These models consider carbon-emission-constraint policies and customer behavior, with distinct customer segments of high-end and low-end preferences.

When refurbished products are sold directly by the manu-facturer through e-channels, wholesale prices for new products tend to be higher. This is driven by the competition between the manufacturer and retailer in attracting consumers. To en-sure their refurbished products remain competitive in terms of pricing, manufactur-ers leverage this opportunity to sell new products to retailers at higher prices. In Model O, when emission capacity is limited and the environmental impact of new products is significant, retailers opt to sell new prod-ucts at lower prices. This allows them to mitigate risks and compete with the manufacturer by offering products at more affordable prices. However, in Model O with larger emission capacity, manu-facturers prefer to increase profits by selling refurbished products at higher prices compared to the third-party involvement in Model T, which faces price competition from retailers. As emission capacity increases, manufacturers prioritize producing new products in Model O and refurbished products in Model T when carbon capacity is limited. Con-versely, when carbon capacity is larger, manufacturers focus on pro-ducing refurbished products in Model O to maximize profits and cover production costs. The profitability of each player improves as carbon emission capacity increas-es, with manufacturers benefiting more in Model O and retailers in Model T.

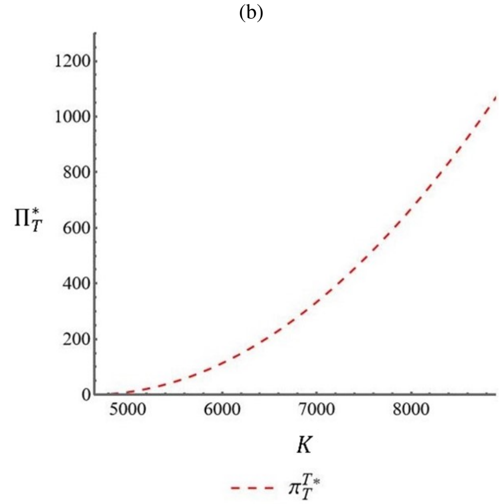
The findings and insights presented in this study pave the way for several in-triguing directions for future research. First and foremost, the dearth of literature on manufactur-ers' distribution channel decisions and their environmental impacts un-derscores the need for further investigation in this area. Delving deeper into how manufacturers, especially prominent ones like Apple, Canon, HP, and Panasonic, make



(a)



(b)



(c)

Fig. 5: Effects of K on total profit of (a) manufacturer, (b) retailer, and (c) third-party.

choices regarding their distribution channels for remanufactured products and the broader environmental implications of these decisions could uncover critical insights for sustainable business practices. Additionally, future research could ex-plore the evolving landscape of carbon-emission-constraint policies and their influ-ence on manufacturers' strategies, considering the dynamic interplay of environmen-tal regulations and market competitiveness. Furthermore, examining how customer behavior, particularly within the high-end and low-end customer segments, shapes manufacturers' distribution channel choices and impacts their profitability could provide a more nuanced understanding of the consumer-driven aspects of this com-plex ecosystem. In conclusion, future research can build upon this foundation to offer a comprehensive and up-to-date perspective on manufacturers' distribution channel decisions, environmental performance, and their implications for both busi-nesses and environmental sustainability.

ACKNOWLEDGMENTS

The authors would like to express the gratitude to The Directorate of Research, Technology and Community Service, Directorate General of Higher Education Re-public of Indonesia for funding this research under the grant scheme numbers 180/E5/PG.02.00.PL/2023, 040/SP2H/RT-MONO/LL4/2023, and III/LPPM/2023-07/122-PE. Counterpart funds from the Institute of Research and Community Service Parahyangan Catholic University under the grant scheme number III/LPPM/2023-06/112-P are greatly appreciated.

REFERENCES

[1] X. Pan, C. W. Y. Wong, and C. Li, "Circular economy practices in the waste electrical and electronic equipment (WEEE) industry: A systematic review and future research agendas," *J. Clean. Prod.*, 2022.
[2] S. Yin, F. Jia, L. Chen, and Q. Wang, "Circular economy practices and sustainable performance: A meta-analysis," *Resour. Conserv. Recycl.*, 2023.
[3] X. Pan, C. W. Y. Wong, and C. Li, "Circular economy practices in the waste electrical and electronic equipment (WEEE) industry: A systematic review and future research agendas," *J. Clean. Prod.*, 2022.
[4] D. Singhal, S. Tripathy, and S. K. Jena, "Remanufacturing for the circular economy: Study and evaluation of critical factors," *Resour. Conserv. Recycl.*, vol. 156, 2020.
[5] N. Saxena, B. Sarkar, and S. R. Singh, "Selection of remanufacturing/production cycles with an alternative market: A perspective on waste management," *J. Clean. Prod.*, vol. 245, 2020.
[6] J. Liu, S. Xia, Z. Wang, J. Nie, N. Ameen, C. Yan, and M. K. Lim, "How to balance economic profits and environmental protection: The impacts of cash hedging on remanufacturing firms," *Int. J. Prod. Econ.*, vol. 258, 2023.
[7] X. Hong, L. Wang, Y. Gong, and W. Chen, "What is the role of value-added service in a remanufacturing closed-loop supply chain?" *Int. J. Prod. Res.*, vol. 58, pp. 3342–3361, 2020.
[8] S. Mitra and S. Webster, "Competition in remanufacturing and the effects of government subsidies," *Int. J. Prod. Econ.*, vol. 111, pp. 287–298, 2008.
[9] N. A. Kurdhi, S. S. Dabadghao, and J. C. Fransoo, "Revenue management in a refurbishing duopoly with cannibalization," *J. Oper. Manag.*, 2022.
[10] Y. Wang, X. Yin, Q. Du, S. Jia, Y. Xie, and S. He, "Consumers' green preferences for remanufactured products," in *Commun. Comput. Inf. Sci.*, Springer Verlag, 2018, pp. 332–342.
[11] X. Xia, M. Li, and W. Wang, "Impact of three emission reduction decisions on authorized remanufacturing under carbon trading," *Expert Syst. Appl.*, vol. 216, 2023.
[12] Q. Wang, B. Li, B. Chen, Z. Wang, W. Liu, and Y. Cheng, "Impact of product design on remanufacturing under environmental legislation," *Comput. Ind. Eng.*, vol. 165, 2022.
[13] X. Xia, M. Lu, and W. Wang, "Emission reduction and outsourcing remanufacturing: A comparative study under carbon trading," *Expert Syst. Appl.*, vol. 227, 2023.
[14] Y. Chen, B. Li, G. Zhang, and Q. Bai, "Quantity and collection decisions of the remanufacturing enterprise under both the take-back and carbon emission capacity regulations," *Transp. Res. E Logist. Transp. Rev.*, vol. 141, 2020.
[15] A. Ghosh, J. K. Jha, and S. P. Sarmah, "Optimal lot-sizing under strict carbon cap policy considering stochastic demand," *Appl. Math. Model.*, vol. 44, pp. 688–704, 2017.
[16] Q. Wang, B. Li, B. Chen, Y. Cheng, and Z. Wang, "Implication of take-back and carbon emission capacity regulations on remanufacturing in a competitive market," *J. Clean. Prod.*, vol. 325, 2021.
[17] J. Xu, Q. Qi, and Q. Bai, "Coordinating a dual-channel supply chain with price discount contracts under carbon emission capacity regulation," *Appl. Math. Model.*, vol. 56, pp. 449–468, 2018.
[18] Y. Huang, S. Liu, and Y. Liang, "Government policies for e-commerce supply chain with fairness concerns towards sustainable remanufacturing," *Kybernetes*, 2022.
[19] Y. Wang, D. Wang, T. C. E. Cheng, R. Zhou, and J. Gao, "Decision and coordination of E-commerce closed-loop supply chains with fairness concern," *Transp. Res. E Logist. Transp. Rev.*, vol. 173, 2023.
[20] W. Yan, Y. Xiong, Z. Xiong, and N. Guo, "Bricks vs. clicks: Which is better for marketing remanufactured products?" *Eur. J. Oper. Res.*, vol. 242, pp. 434–444, 2015.
[21] E. C. McKie, M. E. Ferguson, M. R. Galbreth, and S. Venkataraman, "How do consumers choose between multiple product generations and conditions? An empirical study of iPad sales on eBay," *Prod. Oper. Manag.*, vol. 27, pp. 1574–1594, 2018.
[22] C. Ke and B. Yan, "Trade-in value effects of used products in remanufacturing with considering consumer purchase behavior," *J. Oper. Res. Soc.*, vol. 73, pp. 608–633, 2022.
[23] A. G. Belbağ and S. Belbağ, "Remanufactured products: A systematic review from the consumer perspective," *J. Clean. Prod.*, 2023.
[24] Z. Wang, Y. Duan, and J. Huo, "Impact of trade-in remanufacturing policy and consumer behavior on remanufacturer decisions," *Sustainability*, vol. 12, 2020.
[25] A. Ovchinnikov, "Revenue and cost management for remanufactured products," *Prod. Oper. Manag.*, vol. 20, pp. 824–840, 2011.