

## Article

# A Two-Stage Closed-Loop Supply Chain Pricing Decision: Cross-Channel Recycling and Channel Preference

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**Abstract:** This paper focuses on the pricing problem of a two-stage closed-loop supply chain (CLSC) considering the cross-channel recycling and channel preference based on a single manufacturer and a single traditional retailer. The pricing decision problem raises from the manufacturer's direct sales and the retailer's retailing including recycling. Managers need to focus on intelligible management considering consumer channel preferences, cross-channel recovery and pricing strategies. According to game theory, centralized and decentralized CLSC decision models are used to provide an efficient solution to managers for the pricing problem. The centralized model consists of differential and uniform pricing strategy and the decentralized model consists of manufacturer-led Stackelberg, retailer-led Stackelberg and Nash equilibrium game, respectively. The impact of cross-channel recycling rate and channel preference on pricing and profitability in a two-stage CLSC system is explained elaborately in this study. The results show that cross-channel recovery rates and consumer channel preferences have a direct significant impact on pricing strategies including profit allocation decisions in CLSC. It demonstrated that different channel preferences leading to different pricing strategies and decision for manufacturers and retailers choices. Manufacturer's pricing decreases when channel preferences are constant and cross-channel recovery rates increase. Retailer's pricing remains stable as the cross-channel recovery rate has less affected on it. Furthermore, if the cross-channel recovery rates increase, then the manufacturers pricing decreases and retailers pricing increases. This information will be a helpful guideline for the manager to select suitable pricing strategies based on the company scenario.

**Keywords:** centralised decision-making; closed-loop supply chain; cross-channel recycling; decentralised decision-making; pricing decisions



**Citation:** Pan, W.; Lin, M. A Two-Stage Closed-Loop Supply Chain Pricing Decision: Cross-Channel Recycling and Channel Preference. *Axioms* **2021**, *10*, 120. <https://doi.org/10.3390/axioms10020120>

Academic Editor: Palle E.T. Jorgensen

Received: 25 April 2021

Accepted: 9 June 2021

Published: 15 June 2021

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## 1. Introduction

Based on technological advancement and consumer demand, new products are being introduced to the market at a faster rate; similarly, at the same time producing more products need to be recycled [1,2]. Used and discarded products have potential resource value and environmental risks [3]. Followed by the sustainable development goal, several industries are trying to reduce their environmental impact by incorporating safe environmental concerns in the supply chain operations, such as green innovation, green manufacturing, reusing and recycling [4–7]. Smart manufacturing plays a vital role to create an environment-friendly supply chain [8,9].

The supply chain system is a complex process that requires efficient coordination and smart design from the involved players [10–15]. The process of adopting efficient solutions in the CLSC is time consuming and can lead to several problems that demotivated managers from continuing their efforts to implement smart solutions. Furthermore, the CLSC enhances the level of complexities by the remanufacturing process [16–18]. The modern circular economy, day by day, replacing the “take, make, consume, and throw away” concept with CLSC by combining numerous processes, including maintenance,

repair, refurbishing, remanufacturing, reusing and recycling, which is a worldwide hot research topic for both industry and academia [19–22]. Several countries already started recycling second-hand and waste products, but the current state of that development is not optimistic. In this case, all aspects of the recycling system still need to further improve. Due to the rapid development of e-commerce, the traditional retail industry has been impacted. To enhance their competitiveness, many companies started to improve customer service and satisfaction [23,24]. Therefore, providing more convenient recycling services has become the first choice of companies.

In a dual-channel CLSC system, traditional retail channels co-exist with direct online sales by manufacturers, where consumer's choice of recycling channels may not necessarily coincide with their purchase channels [25–30]. The current new retail era emphasises the combination of online and offline recycling channels to accomplished collaboration between retailers and manufacturers [31–35]. It helps to achieve cross-channel recycling, which improves consumer loyalty and satisfaction, as well as achieve efficient operation of CLSC recycling [36–39]. Under the traditional recycling model for both online and offline sale, the intact second-hand products can be sold through retailers into the second-hand market and used products can be recycled through manufacturers for reprocessing and reuse.

Cross-channel recycling can provide more choices to consumers for recycling channels, which satisfyies different consumers' willingness to recycle. As rational economic agents, some consumers choose to purchase through channels that may not be the same as the recycling service channels. Therefore, adaptively based on consumers preference will be helpful for the maximum benefit [40].

In the dual-channel, the CLSC structure has no direct sales between the manufacturer and the retailer. A large number of studies analysed this type of structure and conducted in-depth research on price [41,42], service [43,44] and product availability [45] competition under dual channels. Most of these studies are based on a decentralised or centralised dual oligopoly CLSC system, where every decision-maker tries to find out their maximum own profit [46].

An efficient pricing strategy will be helpful to increase profits for a better market share of the industry. Thus, the industry pays high attention to the pricing strategy to cover static or dynamic pricing. In dynamic pricing, once the product demand and the other factors are disclosed then making pricing decisions, which lead to the best pricing policy for players for dynamic and uncertain market [47]. Dynamic pricing strategy is considered an influential model to provide higher benefits. This is internationally recognized among experienced firms due to rapid product updates and e-commerce development. The benefit of dynamic pricing reported in the traditional supply chain as well [48,49]. However, dynamic pricing application and its influences on the CLSC is still unknown which include new products and remanufactured goods.

For a dual-channel supply chain, the manufacturers and the retailers try to set products price under different competition models, which is a key focus in supply chain management. In summary, existing two-stage CLSC study are more likely to research pricing strategies and different recycling channel strategies. However, a research gap found in the use of cross channel recycling and channel preference together on CLSC for pricing and profitability, which is very important for the managers.

Specifically, this research addresses the following research questions:

- (1). What is the impact of cross-channel recycling rate on pricing and profitability in a two-stage CLSC system?
- (2). What is the impact of channel preference on pricing and profitability in a two-stage CLSC system?

This paper aims at finding the answers to the aforementioned research questions, according to centralized and decentralized CLSC decision considering the cross-channel recycling and channel preference based on a single manufacturer and a single traditional retailer.

The article is organized as follows: In Section 2, the literature review is discussed. Section 3 contains the model description and basic assumptions. Section 4 provides the detail of model analysis. Section 5 explains the simulation numerical analysis with an

example. Finally, Section 6 gives the conclusion and suggestions that are drawn for future work.

## 2. Literature Review

In this section, the detailed literature review related to this research has been explained. According to the literature review on recycling and pricing decisions, a CLSC is explored. This literature review will be a helpful guide to find out the research gap, which may fulfil by this research.

In terms of dual-channel pricing decisions based on the Bertrand game and the Stackelberg game, the article [50] analysed efficient pricing decisions by comparing dynamic and static dual-channel supply chain pricing models. These models are mostly based on the relevant factors that influence supply chain decisions such as price [51] and service [52]. Apart from that, further enhancement of this research is conducted in [53] to express the investigated price-setting strategy of a dual-channel supply chain in the context of disrupted market demand. In article [8], the advantages and disadvantages of direct sales channels are investigated compared to the optimal pricing decision under the dual and single-channel supply chains, which demonstrated a basis for pricing decisions. Article [54] studied pricing decisions and coordination in a CLSC with mixed channels by assuming that supply chain participants are fully rational and found profit maximization as their decision goal. However, this study finding did not consider the behavioural characteristics of the participants and ignored the influence of the behavioural tendencies of node members on pricing decisions.

Article [55] studied the construction of a dual-channel supply chain decision model under simultaneous cost and demand perturbations, which consider as an optimal pricing equilibrium solution. The price-setting strategies and profit allocation problems under various decisions for different product recovery models in a two-tier CLSC composed of manufacturers and distribution retailers are analysed in [56]. The pricing strategies of CLSCs under government subsidy support for their sales and recycling channels to settle the different government subsidy coefficients, which have different degrees of influence on the profit allocation and price setting strategies in the supply chain are explained in [57,58].

In terms of competition in recycling channels, the article [59] consider the difference in recycling costs between recyclers and manufacturers. They find out how the government can implement effective control over product recycling to make it cheaper when recyclers and manufacturers are separately responsible for recycling. The article [60] studied product recycling from a consumer perspective and modelled the CLSC considering recycling-sensitive and price-sensitive customer behaviour. Article [61] constructed a two-stage CLSC model based on a product recycling performance perspective. In this model, manufacturers carry out product manufacturing and sales operations, but recyclers are responsible for product recycling. Zhang [62] constructed a three-stage CLSC model by using the principal-agent theory to construct a recycling incentive contract model from remanufacturers to recyclers. Article [63] allocated the positive sales revenue and the negative recycling revenue to maximise the profits for both manufacturers and retailers in the CLSC system, thus achieving a win-win situation. Jiang Shiyong [64] constructed a two-level green supply chain model for manufacturers and retailers based on different power structures to analysed the pricing strategies. This model produce green decisions of supply chain by considering four different power structures. Meng [65] used recycling risk as a perspective to compare the CLSC decision-making options of manufacturers own recycling and third-party recycling. Huang [66] studied the choice of vertical cooperative recycling model in a CLSC by constructing a supply chain game model with cost-sharing and task-sharing among manufacturers. Table 1 represents the summarized information of the previous relevant studies.

In summary, existing two-stage CLSC are more likely to study pricing strategies and different recycling channel strategies; however, very limited research exists to examining cross channel recycling. Considering the existence of cross-channel recycling, in reality,

this study extends the existing supply chain channel recycling choice problem. Therefore, this paper designs a cross channel recycling CLSC structure model constructed by a single manufacturer and a single traditional retailer by consumer channel preferences and uses both centralised and decentralised decision-making models to analyse the CLSC decision-making study.

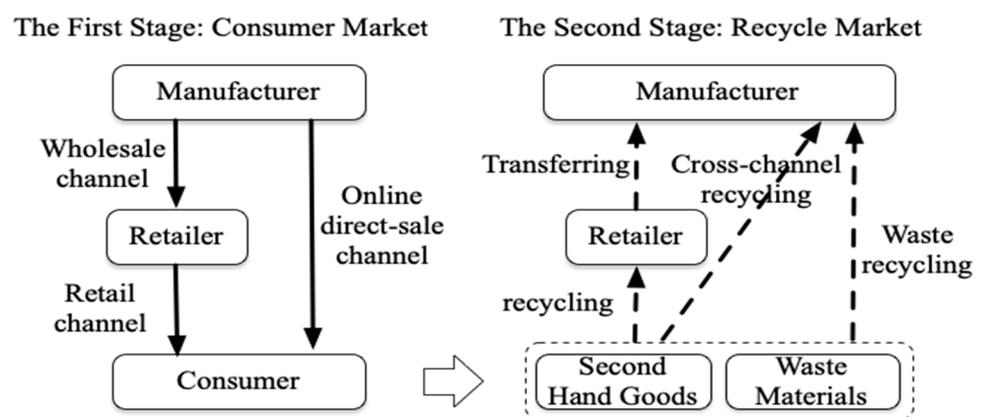
**Table 1.** Summary of previous studies.

References	Variables	Theory	Intervention Policy
Liu et al. [67]	Manufacturing cost; demand	Stackelberg	Price
Alamdar et al. [68]	Sales dependent demand	Nash	Price
Hafezalkotob [69]	Policies; investment; financial benefits	Stackelberg	Social welfare
Fallah et al. [70]	Self-price and cross-price elasticity coefficients; demand; profits	Stackelberg	Price
Wang [71]	Consumer demand; manufacturing cost	Stackelberg	Warranty service
Moradinasab et al. [72]	Profits; environmental pollution	Stackelberg; Nash	Price
Hafezalkotob [73]	manufacturer cost; demand	Stackelberg	Price
Yang et al. [74]	Market scale; manufacturer profit; retailer profit;	Stackelberg	Price
Sheu et al. [75]	price elasticity; sensitivity coefficient of the product	Nash	Price
Reza-Gharehbagh et al. [76]	Wholesale-price; taxation	Stackelberg	Price
Zhao et al. [77]	lending-investment; debt financing; equity financing	Stackelberg; Nash	Price
Mahmoudi et al. [78]	Customer demands; manufacturing cost; service cost coefficients	Stackelberg	Price
	Profit; product targets	Stackelberg	Price

### 3. Model Description and Basic Assumptions

In this paper, CLSC is designed based on a single manufacturer and a single traditional retailer.

Figure 1 showed a two-stage CLSC structure by considering single manufacturing with a selling supply chain and a single recycling reverse supply chain. In the first stage of the forward supply chain structure for the consumer market, mainly two channels co-exist. The first one is the traditional retail channel where the manufacturer sells the product  $\omega$  to the retailer at a wholesale price. After that, the retailer sells the product to the consumer at a retail price  $p_r$ . The second one is the online direct channel where the manufacturer sells the product to the consumer at a price  $p_m$ .



**Figure 1.** Two-stage CLSC structure considering cross-recycling channels.

In the second stage of the reverse supply chain structure for the recycling market, mainly two types of recycling channels exist. Firstly, the manufacturer-recycling channel recycles the used products and makes a profit through remanufacturing. Secondly, the retailer-recycling channel recycles second-hand products and makes a profit through the second-hand trading market. In the manufacturer recycling channel, per unit recycle cost is  $h_m$ . Similarly, in the retailer recycling channel, per unit recycle cost is  $h_r$ . After recycled by the retailer the product transfer to manufacturers at a price  $\bar{\omega}$ . A proportion of

consumers also dispose of second-hand products as waste, i.e., the manufacturer recycles across channels at a per-unit recycling cost  $h_{rm}$ . Conversely, some used products cannot be recycled using the retailer channel because of the mismatch between the value of used products and intact products. Table 2 explained the description of terms and the parameter notation used in this paper.

**Table 2.** Description of parameters.

Symbols	Description
$k_r$	The recovery rate of intact products in the retailer recovery channel.
$k_m$	The recycling rate of used products in manufacturers recycling channels.
$\varepsilon$	Manufacturer cross-channel recovery rates for intact product recovery.
$D_r$ and $D_m$	Demand for products from retailer and manufacturer channels, respectively.
$\alpha$ , $\alpha_r$ , and $\alpha_m$	Total market demand, potential market demand from retailers, and potential market demand from manufacturers, respectively.
$\theta$	Consumer preference for visiting a retailer’s physical shop.
$\beta$ and $\gamma$	Channel ownership prices and cross-price sensitivity, respectively.
$\omega$ and $\bar{\omega}$	Manufacturer’s wholesale price and retailer’s transfer price for the recycled product, respectively.
$p_r$ and $p_m$	Retailer’s retail prices and manufacturer’s direct sales prices, respectively.
$c_m$ , $t$ , and $s$	Manufacturing costs, the value of intact products sold on the secondary market, and profit from the recycling of discarded products, respectively.
$h_j(j = r, m, rm)$	The cost of recycling disposal is $h_j$ . Here, $j = r$ denoting the retailer-recycling channel, $j = m$ denoting the manufacturer-recycling channel, and $j = rm$ denoting the manufacturer cross-channel recycling channel for intact products.
$\pi$ , $\pi_r$ , and $\pi_m$	Total CLSC profit, retailer brick-and-mortar profit, and manufacturer online shop profit, respectively.
$P_r^{C*}$	The convex function of consumer channel preference based on retailer’s pricing
$P_m^{C*}$	The concave function of consumer channel preferences based on manufacturer’s pricing
$\omega^{M*}$	Manufacturer’s wholesale price under Manufacturer-led Stackelberg game
$P_m^{M*}$	Manufacturer’s direct selling price under Manufacturer-led Stackelberg game
$P_r^{M*}$	Manufacturer’s retail price under Manufacturer-led Stackelberg game
$\omega^{R*}$	Manufacturer’s wholesale price under Retailer-led Stackelberg game
$P_m^{R*}$	Manufacturer’s the direct selling price under Retailer-led Stackelberg game
$P_r^{R*}$	Manufacturer’s the retail price under Retailer-led Stackelberg game
$\omega^{N*}$	Manufacturer’s wholesale price under Nash equilibrium game
$P_m^{N*}$	Manufacturer’s direct selling price under Nash equilibrium game
$P_r^{N*}$	Manufacturer’s retail price under Nash equilibrium game
$P_m^C$	Manufacturer pricing under differential pricing
$P_r^C$	Retailer pricing under differential pricing
$P_r^{MLSG}$	Retailer pricing under manufacturer-led
$P_r^{RLSG}$	Retailer pricing under retailer-led
$P_r^{NG}$	Retailer pricing under Nash equilibrium
$P_m^{MLSG}$	Manufacturer pricing under manufacturer-led
$P_m^{RLSG}$	Manufacturer pricing under retailer-led
$P_m^{NG}$	Manufacturer pricing under Nash equilibrium
$\pi_m^{MLSG}$	Manufacturer’s profit size under the manufacturer-led model
$\pi_m^{RLSG}$	Manufacturer’s profit size under the retailer-led model
$\pi_m^{NG}$	Manufacturer’s profit size under Nash equilibrium model

As the retailer and the manufacturer recycling channel handle products differently, so their recycling profits are also captured differently. The disposal value of intact products sold on the secondary market being  $t(t \geq \bar{\omega} \geq h_r)s$  and the profit from recycling and remanufacturing of waste products being  $(s \geq h_m)$ . In addition, intact products recycled across channels through the manufacturer’s recycling channel at a price of  $h_m$ . However, their value after recycling and disposal is the same as the value of the retailer’s recycling channel, which is valued at  $t$ , where the condition is satisfied as  $t > s$ . The cost of recycling disposal for the recycling channel  $R_j(j = r, m, rm)$  is  $h_j(j = r, m, rm)$ .

The symbol  $D_r$  and  $D_m$  denote total product sales in the retailer’s physical shop and the manufacturer’s online shop, respectively. From a market size perspective, shops will not

longer sell products once the total consumer demand has been fulfilled. The parameter  $\alpha$  indicates the maximum potential market demand. Here, assume  $0 \leq \theta \leq 1$  is the consumer preference for the retailer channel and  $\alpha_r = \alpha\theta$  for the retailer's base sales volume. Similarly, the assumption  $1 - \theta$  is the manufacturer's channel preference and manufacturer follow  $\alpha_m = \alpha(1 - \theta)$ ,  $D_r = \alpha_m - \beta p_r + \gamma p_m$  and  $D_m = \alpha_m - \beta p_m + \gamma p_r$ . The parameters  $\beta$  and  $\gamma$  measure the price elasticity of demand concerning its price and cross-price sensitivity, respectively. In addition, assuming that  $\beta$  and  $\gamma$  satisfy  $\beta > \gamma > 0$ , which means that the quantity demanded of a product is more sensitive to changes its own channel price compare to changes in the price of products in other channels [79].

The recycling rate is assumed to be  $k(0 \leq k \leq 1)$ , where the recycling rate of intact products in the retailer recycling channel is  $k_r$ . The recycling rate of used products in the manufacturer-recycling channel is  $k_m$  and the recycling rate of intact products recycled using the manufacturer cross-channel is  $\varepsilon$ . These are satisfied the following condition as  $k = k_r + k_m + \varepsilon$ . The number of intact products recycled by retailers is  $k_r(D_m + D_r)$ , the number of used products recycled by manufacturers is  $k_m(D_m + D_r)$  and the number of intact products recycled by manufacturers across channels is  $\varepsilon(D_m + D_r)$ .

In this paper, we constructed a two-stage dual-channel CLSC structure and analyse the impact of channel preference and cross-channel recovery rate on the price and profit of the CLSC using centralised and decentralised decision-making. The centralised decision-making is divided into two types, such as differential pricing strategy and uniform pricing strategy, which seek to maximise the total profit of the CLSC from the supply chain as a whole. Similarly, the decentralised decision-making consists of three models such as the manufacturer-led Stackelberg game, the retailer-led Stackelberg game and the Nash equilibrium game. In the manufacturer-led Stackelberg game, the manufacturer first determines its direct sales price and then the physical retailer announces its selling price. In the retailer-dominated Stackelberg game, the retailer's physical shop first announces its selling price and the manufacturer then determines its direct selling price. In the Nash equilibrium game, both channels are equally powerful in terms of price determination, so the manufacturer and the retailer set their price strategies simultaneously.

## 4. Model Analysis

### 4.1. Centralized Decision Model

In a centralised decision-making model, the manufacturer and retailer determine the optimal profit for the CLSC [80–82]. Both parties cooperate instead of competing to determine the optimal pricing to maximise the total CLSC profit  $\pi$ . They determine the retailer's retail price  $p_r$  and the manufacturer's direct sales price  $p_m$ .

$$\pi = (p_m - c_m)D_m + (p_r - c_m)D_r + ((s - h_k)k_m + (t - h_r)k_r + (t - h_{rm})\varepsilon)(D_m - D_r) \quad (1)$$

The total profit function for the CLSC in the centralised decision-making model is expressed in Equation (1). The centralised decision-making consists of differential pricing strategy and uniform pricing strategy, which are described below.

#### 4.1.1. Differential Pricing Strategies

Centralised decision-making is the result of manufacturers and retailers seeking a win-win partnership [83–85]. However, different entities have different costs and their profit varies. In this case, differential pricing strategies are chosen to reduce the uneven distribution profits, which help to maximise overall profits. Differential pricing is the best strategy for allocating the highest price to the channel with the highest operating costs. It requires consideration of price-sensitive consumer behaviour, where the pricing strategy should be proportional to consumer preferences and the services offers. Therefore, this section applies differential pricing strategies to investigate the impact of consumer preferences and recovery rates on pricing policies in a dual-channel CLSC.

**Proposition 1.** Under a differential pricing strategy in CLSC, the total profit  $\pi$  is a strictly concave function concerning  $p_m$  and  $p_r$ .

The optimal price for the retailer expressed as  $P_r^{c*}$  which is calculated by Equation (2). Similarly, the optimal price for the manufacturer’s direct sales expressed as  $P_m^{c*}$ , which calculated by Equation (3).

$$P_r^{c*} = \frac{1}{2} \left[ \frac{c_m(\gamma + \beta) + \alpha_r - \alpha_m}{\gamma^2 - \beta^2} \times \gamma - \frac{\alpha_r + \beta c_m}{\gamma - \beta} - A \right] \tag{2}$$

$$P_m^{c*} = \frac{1}{2} \left[ \frac{c_m(\gamma + \beta) + \alpha_m - \alpha_r}{\gamma^2 - \beta^2} \times \gamma - \frac{\alpha_m + \beta c_m}{\gamma - \beta} - A \right] \tag{3}$$

Here,  $A = (s - h_m)k_m + (t - h_r)k_r + (t - h_{rm})\varepsilon$ .

**Proof.** By solving for the Hesse matrix, we get Equation (4).

$$H_c = \begin{pmatrix} \frac{\partial^2 \pi^c}{\partial p_r^2} & \frac{\partial^2 \pi^c}{\partial p_r \partial p_m} \\ \frac{\partial^2 \pi^c}{\partial p_m \partial p_r} & \frac{\partial^2 \pi^c}{\partial p_m^2} \end{pmatrix} = \begin{pmatrix} -2\beta & 2\gamma \\ 2\gamma & -2\beta \end{pmatrix} = 4\beta^2 - 4\gamma^2 \tag{4}$$

$$\frac{\partial \pi^c}{\partial p_r} = (2p_m - c_m)\gamma + \alpha_r - \beta(2p_r - c_m) + A(\gamma - \beta) \tag{5}$$

$$\frac{\partial \pi^c}{\partial p_m} = (2p_r - c_m)\gamma + \alpha_r - \beta(2p_m - c_m) + A(\gamma - \beta) \tag{6}$$

$$\frac{\partial^2 \pi^c}{\partial p_r^2} = -2\beta, \quad \frac{\partial^2 \pi^c}{\partial p_m^2} = -2\beta \tag{7}$$

From Equation (7), it follows that  $\frac{\partial^2 \pi^c}{\partial p_r^2} < 0$ ,  $\frac{\partial^2 \pi^c}{\partial p_m^2} < 0$ , so the total CLSC of profit is a strictly concave function on  $p_m$  and  $p_r$ . Since  $|H_c| > 0$ , as a result,  $\beta > \gamma$  consistent with the hypothesis. By using Equations (5) and (6) we can solve Equations (2) and (3) as follow.

$$\begin{cases} (2p_m - c_m)\gamma + \alpha_r - \beta(2p_r - c_m) + A(\gamma - \beta) = 0 \\ (2p_r - c_m)\gamma + \alpha_r - \beta(2p_m - c_m) + A(\gamma - \beta) = 0 \end{cases}$$

By following Proposition 1, the optimal equilibrium cannot be solved, when  $\gamma$  has infinite converges to  $\beta$ , or when the recovery rates of the different channels are severely imbalanced. In addition, the recovery rates of different channels affect the decision choice of a two-stage CLSC.

The effect of different consumer channel preferences  $\theta$  on the equilibrium price is greater due to  $\frac{\partial P_r^{c*}}{\partial \theta} = \frac{1}{2} \times \frac{\alpha}{\beta + \gamma} > 0$  and  $\frac{\partial P_m^{c*}}{\partial \theta} = -\frac{1}{2} \times \frac{\alpha}{\beta + \gamma} < 0$ . Here,  $P_r^{c*}$  is a convex function of consumer preference and retailer’s pricing increases as  $\theta$  increases. Conversely,  $P_m^{c*}$  is a concave function of consumer channel preferences, the manufacturer’s pricing decreases as  $\theta$  increases. This suggests that the magnitude of  $\theta$  change in manufacturer and retailer pricing depends on  $\frac{\alpha}{2(\gamma + \beta)}$  magnitude.

Based on  $\left| \frac{\partial P_r^{c*}}{\partial \theta} \right| = \left| \frac{\partial P_m^{c*}}{\partial \theta} \right|$ , it is clear that if the  $\theta$  magnitude changes then channel preference is the same. Moreover, manufacturer and retailer pricing fluctuations are also the same.  $\square$

**Corollary 1.** Under a centralized differential pricing strategy,  $\bar{\theta} = \frac{1}{2} P_m^{c*} = P_r^{c*}$  exists.

#### 4.1.2. Uniform Pricing Strategy

Under centralised decision-making, differential pricing strategies can easily lead to conflicts between channels due to differences in pricing [86]. Therefore, two-stage CLSC under centralised decision making will require for uniform pricing strategy on a per-

volume basis [33,87], where exists  $P_r = P_m = P$ . In this section, further analysing on the impact of consumer channel preferences as well as recovery rates for pricing policies have been explained.

**Proposition 2.** Under a uniform pricing strategy in CLSC, the total profit  $\pi$  is a strictly concave function concerning  $P$ .

The optimal uniform pricing price  $P^{U*}$  is expressed by Equation (8).

$$P^{U*} = \frac{1}{2}c_m - \frac{\alpha_r + \alpha_m}{4(\gamma - \beta)} - \frac{1}{2}A \tag{8}$$

Here,  $A = (s - h_m)k_m + (t - h_r)k_r + (t - h_{rm})\epsilon$ .

**Proof.** Since  $P_r = P_m = P$ , therefore,  $D_r = \alpha_r - p(\beta - \gamma)$ ,  $D_m = \alpha_m - p(\beta - \gamma)$ . Solve the first and second-order derivatives of the price  $P$  concerning the total profit of the CLSC as below.

$$\frac{\partial \pi}{\partial p} = \alpha_r + \alpha_m - 2p(\beta - \gamma) + 2(\gamma - \beta)(P - c_m + A), \quad \frac{\partial^2 \pi}{\partial p^2} = 4(\gamma - \beta) < 0$$

So the total CLSC profit  $\pi$  is a strictly concave function concerning  $P$ . Let the first-order derivative  $\frac{\partial \pi}{\partial p} = 0$  for solving  $p = \frac{1}{2}c_m - \frac{\alpha_r + \alpha_m}{4(\gamma - \beta)} - \frac{1}{2}A$ .

Proposition 2 shows that  $\frac{\partial P}{\partial \theta} = -\frac{\alpha - \alpha}{4(\gamma - \beta)} = 0$ . Here, consumer channel preferences do not affect the uniform pricing strategy of a CLSC. However, the change in uniform pricing  $P^{U*}$  are mainly related to the recovery rates of different channels.  $\square$

**Corollary 2.** Under a uniform pricing strategy, consumer channel preference has no impact on the total profitability of the CLSC. The uniform price is related to the magnitude of  $k_m, k_r$  and  $\epsilon$  recovery rate across channels.

#### 4.2. Decentralised Decision Model

In a centralised decision-making model, the CLSC is categorised by good cooperation and a willingness to share high operating costs, which unable to make optimal profits [86]. However, in reality, the supply chain follows both cooperative and competitive criteria. In a highly competitive environment, every company is driven by its principle for maximising its profits. In this circumstance, decentralised decision-making is a better fit with practical reality [88–90]. In addition, cross-channel recycling increases the choice of recycling channels available to consumers and enhances their product recycling experience.

The total profit of a CLSC under decentralised decision-making consists of two parts such as the total profit of the manufacturer and the total profit of the retailer.

The formula for the manufacturer’s total profit function is expressed by Equation (9).

$$\pi_m = (p_m - c_m)D_m + (\omega - c_m)D_r + [(s - h_m)k_m + (t - h_{rm})\epsilon + (t - \bar{\omega})k_r](D_m + D_r) \tag{9}$$

The formula includes the following components: profit on sales in the direct sales channel, profit on wholesale and profit on recycled products in the three different recycling channels.

The formula for the retailer’s total profit function is expressed by Equation (10).

$$\pi_r = (p_r - \omega)D_r + (\bar{\omega} - h_r)k_r(D_r + D_m) \tag{10}$$

The formula consists of the following main components: the retailer’s profit on sales and the profit earned by the retailer from recycling products from the recycling channel.

### 4.2.1. Manufacturer-Led Stackelberg Game (MLSG)

With the advent of the new retail era, traditional retailers are facing various challenges. Due to cost control factors, manufacturers have a huge advantage in selling online over retailers and manufacturers are often in a dominant position to influence retailer’s price setting in the CLSC. Mainly the manufacturers determined the direct sales price in the MLSG [91–93]. In this case, of MLSG the retailer only able to set its retail price after the manufacturer’s direct price has been set.

**Proposition 3.** *In the MLSG, the optimal equilibrium solutions for the manufacturer’s wholesale price  $\omega^{M^*}$ , the direct selling price  $P_m^{M^*}$  and the retailer’s price  $P_r^{M^*}$ , respectively.*

The term  $\omega^{M^*}$ ,  $P_m^{M^*}$  and  $P_r^{M^*}$  formulas have been expressed by Equations (11)–(13), respectively.

$$\omega^{M^*} = \frac{c_m - B}{2} + \frac{\alpha_r + B\gamma - C - \gamma c_m}{2\beta} + \frac{2\beta\gamma a_m + 2\gamma^2(\alpha_r - \gamma c_m) + 2\beta^2\gamma c_m + 2\beta\gamma(\gamma^2 - \beta^2)}{4\beta^3 - \beta^2\gamma^2 - 3\beta\gamma^2} \tag{11}$$

$$P_m^{M^*} = \frac{2\beta a_m + 2\gamma\alpha_r - 2\gamma^2 c_m + 2\beta^2 c_m + 2B(\gamma^2 - \beta^2)}{4\beta^2 - \beta\gamma^2 - 3\gamma^2} \tag{12}$$

$$P_r^{M^*} = \frac{\alpha_r + c}{2\beta} + \frac{\gamma \left[ a_m(1 + \beta) + \alpha_r \left( \frac{\gamma}{\beta} + 1 \right) - \gamma^2 c_m \left( \frac{1}{\beta} + 1 \right) + \beta c_m(1 + \beta) + \left( \frac{B}{\beta} + \beta \right) (\gamma^2 - \beta^2) \right]}{4\beta^3 - \beta^2\gamma^2 - 3\beta\gamma^2} \tag{13}$$

Here,  $B = (s - h_m)k_m + (t - h_{rm})\varepsilon + (t - \bar{\omega})k_r$  and  $C = (\bar{\omega} - h_r)k_r(\gamma - \beta)$ .

**Proof.** By solving the Hesse matrix, it follows Equation (14).

$$H_M = \begin{pmatrix} \frac{\partial^2 \pi_m}{\partial p_m^2} & \frac{\partial^2 \pi_m}{\partial p_m \partial \omega} \\ \frac{\partial^2 \pi_m}{\partial \omega \partial p_m} & \frac{\partial^2 \pi_m}{\partial \omega^2} \end{pmatrix} = \begin{pmatrix} \frac{\gamma^2 - 2\beta^2}{\beta} & \gamma \\ \gamma & -\beta \end{pmatrix} = 2(\beta^2 - \gamma^2) \tag{14}$$

Since  $\frac{\partial \pi_r}{\partial p_r} = \alpha_r - \beta p_r + \gamma p_m - \beta(p_r - \omega) + (\bar{\omega} - h_r)k_r(\gamma - \beta)$  and  $\frac{\partial^2 \pi_r}{\partial p_r^2} = -2\beta < 0$ . So the retailer’s profit  $\pi_r$  is a strictly concave function of the retailer’s price  $p_r$ .  $P_r^{M^*}(p_m, \omega) = \frac{\alpha_r + \gamma p_m + \beta \omega + C}{2\beta}$ , where  $C = (\bar{\omega} - h_r)k_r(\gamma - \beta) \cdot P_r^{M^*}(p_m, \omega)$ . Substituting the total manufacturer-led CLSC profit  $\pi_m$  for solving the first-order derivative and second-order derivative of the manufacturer’s wholesale price and direct sales price concerning the total CLSC as per Equations (15) and (16).

$$\frac{\partial \pi_m}{\partial p_m} = \alpha_r + \gamma \times \frac{\alpha_r + C}{2\beta} - c_m \left( \frac{\gamma^2}{2\beta} - \beta \right) - \frac{\gamma}{2} c_m + B \left( \frac{\gamma^2}{2\beta} - \beta + \frac{\gamma}{2} \right) - \beta p_m + \frac{\gamma^2 p_m}{2\beta} + \left( \frac{\gamma^2}{2\beta} - \beta \right) p_m + \gamma \omega \tag{15}$$

$$\frac{\partial \pi_m}{\partial \omega} = \gamma p_m - \beta \omega - \frac{\gamma}{2} c_m + \alpha_r - \frac{\alpha_r + C}{2} + \frac{\beta c_m}{2} + B \left( \frac{\gamma}{2} - \frac{\beta}{2} \right) \tag{16}$$

Since  $|H_M| > 0$  then hypothesis  $\beta > \gamma$  is satisfied.

Here,  $\frac{\partial^2 \pi_m}{\partial p_m^2} = \frac{\gamma^2 - 2\beta^2}{\beta} < 0$ ,  $\frac{\partial^2 \pi_m}{\partial \omega^2} = -\beta < 0$ ,  $\frac{\partial^2 \pi_m}{\partial p_m \partial \omega} = \gamma$ ,  $\frac{\partial^2 \pi_m}{\partial \omega \partial p_m} = \gamma$ . The  $\pi_m$  is a strictly concave function on  $p_m$  and  $\omega$ . Combining Equations (14) and (15) and making their derivatives equal to 0 is given as below.

$$\begin{cases} \alpha_r + \gamma \times \frac{\alpha_r + C}{2\beta} - c_m \left( \frac{\gamma^2}{2\beta} - \beta \right) - \frac{\gamma}{2} c_m + B \left( \frac{\gamma^2}{2\beta} - \beta + \frac{\gamma}{2} \right) - \beta p_m + \frac{\gamma^2 p_m}{2\beta} + \left( \frac{\gamma^2}{2\beta} - \beta \right) p_m + \gamma \omega = 0 \\ p_m - \beta \omega - \frac{\gamma}{2} c_m + \alpha_r - \frac{\alpha_r + C}{2} + \frac{\beta c_m}{2} + B \left( \frac{\gamma}{2} - \frac{\beta}{2} \right) = 0 \end{cases}$$

$$\omega^{M^*} = \frac{c_m - B}{2} + \frac{\alpha_r + B\gamma - C - \gamma c_m}{2\beta} + \frac{2\beta\gamma a_m + 2\gamma^2(\alpha_r - \gamma c_m) + 2\beta^2\gamma c_m + 2\beta\gamma(\gamma^2 - \beta^2)}{4\beta^3 - \beta^2\gamma^2 - 3\beta\gamma^2}$$

Here,  $\omega^{M^*}$  and  $p_m^{M^*}$  substitute as  $p_r^{M^*}(p_m, \omega)$ .

$$P_m^{M^*} = \frac{2\beta a_m + 2\gamma\alpha_r - 2\gamma^2 c_m + 2\beta^2 c_m + 2B(\gamma^2 - \beta^2)}{4\beta^2 - \beta\gamma^2 - 3\gamma^2}$$

$$P_r^{M^*} = \frac{\alpha_r + c}{2\beta} + \frac{\gamma \left[ a_m(1 + \beta) + \alpha_r \left( \frac{\gamma}{\beta} + 1 \right) - \gamma^2 c_m \left( \frac{1}{\beta} + 1 \right) + \beta c_m(1 + \beta) + \left( \frac{B}{\beta} + \beta \right) (\gamma^2 - \beta^2) \right]}{4\beta^3 - \beta^2\gamma^2 - 3\beta\gamma^2}$$

It follows from Proposition 3 that as below.

$$\frac{\partial \omega^{M^*}}{\partial \theta} = \frac{\alpha}{2\beta} + \frac{2\gamma^2\alpha - 2\beta\gamma\alpha}{4\beta^3 - \beta^2\gamma^2 - 3\beta\gamma^2} > 0 \quad \frac{\partial p_m^{M^*}}{\partial \theta} = \frac{2\alpha(\gamma - \beta)}{4\beta^2 - \beta\gamma^2 - 3\gamma^2} < 0$$

$$\frac{\partial p_r^{M^*}}{\partial \theta} = \frac{\alpha}{2\beta} + \frac{\alpha(\alpha + \beta) - \alpha\gamma\beta(1 + \alpha)}{4\beta^4 - \beta^3\gamma^2 - 3\beta^2\gamma^2} > 0$$

The manufacturer-led optimal price is an increasing function of consumer channel preference  $\theta$ . The manufacturer’s wholesale price  $\omega^{M^*}$  increasing as channel preference  $\theta$  increases. The manufacturer’s direct price  $P_m^{M^*}$  is a decreasing function of consumer channel preference  $\theta$ . The retailer’s retail price  $P_r^{M^*}$  increasing as channel preference  $\theta$  increases. □

**Corollary 3.** *In a manufacturer-led pricing model, the retailer’s pricing strategy for retail prices is the same as the manufacturer’s pricing strategy for direct sales prices.*

When  $\bar{\theta} = \frac{4\beta^2\alpha - 2\gamma(1+\beta)\alpha - 2\beta D}{4\gamma\beta\alpha - 2\alpha^2(1+\beta) + \beta\gamma^2\alpha + 3\alpha\gamma^2 + 2\gamma\alpha + 2\beta D}$ , then there is  $P_m^{M^*} = P_r^{M^*}$ .

#### 4.2.2. Retailer-Led Stackelberg Game (RLSG)

Due to the asymmetry of information, retailers are able to respond more quickly to consumer demand in some sectors. As a result, they hold the led of the sales channel in a CLSC and stay in a dominant position to bargain with manufacturers [94,95]. In an RLSG, the retailer can adjust its retail prices  $P_r$  according to market demand in order to maximise profits. In this case, the manufacturer needs to follow the retailer’s price movements to determine its own wholesale prices  $\omega$  and online shop direct prices  $P_m$ .

**Proposition 4.** *In the RLSG, the optimal equilibrium solutions for the manufacturer’s wholesale price  $\omega^{R^*}$ , the direct selling price  $P_m^{R^*}$  and the retailer’s price  $P_r^{R^*}$ , respectively.*

The term  $\omega^{R^*}$ ,  $P_m^{R^*}$  and  $P_r^{R^*}$  calculating formulas have been expressed by Equations (17)–(19), respectively.

$$\omega^{R^*} = \frac{\gamma\alpha[\beta(1 - \theta) + \gamma\theta]}{2\beta(\beta^2 - \gamma^2)} + \frac{\alpha\theta}{2\beta} - \frac{1}{2} \left( \frac{\alpha\theta}{2\beta} + \frac{G}{\beta} \right) - F \tag{17}$$

$$P_m^{R^*} = \frac{\alpha[(1 - \theta)\beta + \gamma\theta] - E}{2(\beta^2 - \gamma^2)} \tag{18}$$

$$P_r^{R^*} = \frac{1}{2} \left( \frac{\alpha\theta}{2\beta} + \frac{c_m}{\beta} \right) + \frac{\gamma\alpha[\beta(1 - \theta) + \gamma\theta]}{2\beta(\beta^2 - \gamma^2)} + \frac{\alpha\theta}{2\beta} - F \tag{19}$$

Here,  $E = \gamma[\gamma c_m + \beta(B - c_m)] + \beta(\beta - \gamma)(c_m - B)$ ,  $F = \frac{\gamma E}{2\beta(\beta^2 - \gamma^2)} + \frac{\gamma c_m + \beta(B - c_m)}{2\beta}$  and  $G = \beta F - \frac{\gamma E}{2(\beta^2 - \gamma^2)} - \beta(\bar{\omega} - h_r)k_r + (\bar{\omega} - h_r)k_r \gamma + \frac{1}{2}\beta(\bar{\omega} - h_r)k_r$ .

**Proof.** From the proposition, we know that, if the retailer’s expected profit is  $f$ , then the retailer’s pricing will be  $P_r = \omega + f$ . This is obtained by substituting the  $P_r$  manufacturer’s profit  $\pi_m$ .

$$\pi_m = (P_m - c_m)[a_m - \beta P_m + \gamma(f + \omega)] + (\omega - c_m)[\alpha_r - \beta(f + \omega) + \gamma P_m] + B[a_m - \beta P_m + (\gamma - \beta)(f + \omega) + \alpha_r + \gamma P_m]$$

The first-order derivative of the manufacturer’s wholesale price and direct sales price for the manufacturer’s total profit  $\pi_m$  as Equations (20) and (21).

$$\frac{\partial \pi_m}{\partial P_m} = a_m - \beta P_m + \gamma(f + \omega) - \beta(P_m - c_m) + (\omega - c_m)\gamma + B(\gamma - \beta) \tag{20}$$

$$\frac{\partial \pi_m}{\partial \omega} = (P_m - c_m)\gamma + a_r - \beta(f + \omega) + \gamma P_m - \beta(\omega - c_m) - \beta B \tag{21}$$

Combining the Equations (17) and (18) and making their derivatives zero respectively as below.

$$\begin{cases} a_m - \beta P_m + \gamma(f + \omega) - \beta(P_m - c_m) + (\omega - c_m)\gamma + B(\gamma - \beta) = 0 \\ (P_m - c_m)\gamma + a_r - \beta(f + \omega) + \gamma P_m - \beta(\omega - c_m) - \beta B = 0 \end{cases}$$

Solving  $P_m^{R*} = \frac{\alpha[(1-\theta)\beta + \gamma\theta] - E}{2(\beta^2 - \gamma^2)}$ ,  $\omega^{R*}$  and  $P_m^{R*}$  need substituting  $\omega^{R*} = \frac{\gamma\alpha[\beta(1-\theta) + \gamma\theta]}{2(\beta^2 - \gamma^2)} + \frac{\alpha\theta}{2\beta} - \frac{1}{2}\left(\frac{\alpha\theta}{2\beta} + \frac{G}{\beta}\right) - F$ , for the total retailer profit, the first-order derivative of the total retailer profit with  $f$  and  $\pi_r$  based on the expected profit.  $\frac{\partial \pi_r}{\partial f} = \frac{a_r}{2} - \beta f + G$  such that  $\frac{\partial \pi_r}{\partial f} = 0$ , gives  $f = \frac{\alpha\theta}{2\beta} + \frac{G}{\beta}$ . Because  $P_r = \omega + f$ , therefore,  $P_r^{R*} = \frac{1}{2}\left(\frac{\alpha\theta}{2\beta} + \frac{G}{\beta}\right) + \frac{\gamma\alpha[\beta(1-\theta) + \gamma\theta]}{2\beta(\beta^2 - \gamma^2)} + \frac{\alpha\theta}{2\beta} - F$ . Where  $E = \gamma[\gamma c_m + \beta(B - c_m)] + \beta(\beta - \gamma)(c_m - B)$ ,  $F = \frac{\gamma E}{2\beta(\beta^2 - \gamma^2)} + \frac{\gamma c_m + \beta(B - c_m)}{2\beta}$  and  $G = \beta F - \frac{\gamma E}{2\beta(\beta^2 - \gamma^2)} - \beta(\bar{\omega} - h_r)k_r + (\bar{\omega} - h_r)k_r\gamma + \frac{1}{2}\beta(\bar{\omega} - h_r)k_r$ .

According to Proposition 4, the optimal equilibrium solution under retailer dominance is analysed and found the consumer channel preferences  $\frac{\partial \omega^{M*}}{\partial \theta} = \frac{\alpha(\beta - \gamma)}{4\beta(\beta + \gamma)} > 0$ ,  $\frac{\partial P_m^{R*}}{\partial \theta} = -\frac{\alpha}{2(\beta + \gamma)} < 0$  and  $\frac{\partial P_r^{R*}}{\partial \theta} = \frac{3\alpha\beta + \alpha\gamma}{4\beta(\beta + \gamma)} > 0$ .

It follows the manufacturer’s wholesale price as an increasing function regarding consumer preferences  $\theta$ . The manufacturer’s wholesale price  $\omega^{R*}$  increases as channel preferences increase. The manufacturer’s direct sales price is a decreasing function of preference regarding consumer channels. The manufacturer’s direct sales price  $P_m^{R*}$  decreases as channel preferences  $\theta$  increase. The retailer’s price is an increasing function of preference regarding consumer channels and the retailer’s retail price increases as channel preferences increase. The retailer’s price is an increasing function of the consumer channel preference, where the retailer’s retail price  $P_r^{R*}$  increasing as the channel preference increases. □

**Corollary 4.** In an RLSG model, the retailer’s retail price is the same as the manufacturer’s direct sales price when the pricing strategy  $\bar{\theta} = \frac{(4\beta F - 2G)(\beta^2 - \gamma^2) - 2\beta E - 2\alpha\beta(\beta + \gamma)}{\alpha(\beta^2 - \gamma^2)}$ , then  $P_m^{R*} = P_r^{R*}$  exists.

#### 4.2.3. Nash Equilibrium Game Pricing (NG)

In the CLSC of the Nash equilibrium game (NG), the manufacturer  $\omega$   $P_m$  and the retailer has the same strength and no one is in the absolute leading position for  $P_r$ . So, in NG the decisions of both parties depend on each other’s behaviour [96–98].

**Proposition 5.** Under NG pricing, the optimal equilibrium solutions provided for the manufacturer’s wholesale price  $\omega^{N*}$ , the direct selling price  $P_m^{N*}$  and the retailer’s price  $P_r^{N*}$ , respectively.

The term  $\omega^{N*}$ ,  $P_m^{N*}$  and  $P_r^{N*}$  calculating formulas have been expressed by Equations (22)–(24), respectively.

$$\omega^{N*} = \frac{\gamma\beta\alpha_m + 2\beta^2\alpha_r + \beta^2\gamma c_m + \gamma^2[G(\beta - \gamma) - \beta c_m] + \gamma\beta^2 B(\gamma - \beta) + 2\beta^2 G(\beta - \gamma)}{2\beta^3} \tag{22}$$

$$P_m^{N^*} = \frac{\alpha_m \beta + \beta^2 c_m + \gamma [G(\beta - \gamma) - \beta c_m] + B \beta^2 (\gamma - \beta)}{2\beta^2} \tag{23}$$

$$P_r^{N^*} = \frac{\gamma \beta \alpha_m + 2\beta^2 \alpha_r + \beta^2 \gamma c_m + \gamma^2 [G(\beta - \gamma) - \beta c_m] + \gamma \beta^2 B (\gamma - \beta)}{2\beta^3} \tag{24}$$

**Proof.** From the proposition,  $P_r = \omega + f$ . Here,  $P_r$  substitute the total manufacturer’s profit  $\pi_m$ , for the first-order derivative of the total manufacturer’s profit with  $\pi_m$  based on the manufacturer’s wholesale price  $\omega$  and the direct sales price  $P_m$ . The first-order derivative of the retailer’s total profit  $P_r$  concerning retailer’s price  $\pi_r$  as follows.

$$\frac{\partial \pi_m}{\partial p_m} = \alpha_m - \beta p_m + \gamma p_r - \beta(p_m - c_m) + (\omega - c_m)\gamma + B(\gamma - \beta) \tag{25}$$

$$\frac{\partial \pi_m}{\partial \omega} = \alpha_r - \beta p_r + \gamma p_m \tag{26}$$

$$\frac{\partial \pi_r}{\partial p_r} = \alpha_r - \beta p_r + \gamma p_m - \beta(p_r - \omega) + (\bar{\omega} - h_r)k_r(\gamma - \beta) \tag{27}$$

The system of Equations (25)–(27) are combined to write  $\frac{\partial \pi_m}{\partial p_m} = 0$ ,  $\frac{\partial \pi_m}{\partial \omega} = 0$ ,  $\frac{\partial \pi_r}{\partial p_r} = 0$  for solving Equations (22)–(24), respectively.

$$\begin{cases} \alpha_m - \beta p_m + \gamma p_r - \beta(p_m - c_m) + (\omega - c_m)\gamma + B(\gamma - \beta) = 0 \\ \alpha_r - \beta p_r + \gamma p_m = 0 \\ \alpha_r - \beta p_r + \gamma p_m - \beta(p_r - \omega) + (\bar{\omega} - h_r)k_r(\gamma - \beta) = 0 \end{cases}$$

From Proposition 5, it follows that the optimal price under the NG analysed by consumption channel preference,  $\frac{\partial \omega^{N^*}}{\partial \theta} = \frac{2\beta - \gamma \alpha}{2\beta^2} < 0$ ,  $\frac{\partial P_m^{N^*}}{\partial \theta} = -\frac{\alpha}{2\beta} < 0$ ,  $\frac{\partial P_r^{N^*}}{\partial \theta} = \frac{2\beta - \gamma}{2\beta^2} > 0$ .

The manufacturer’s wholesale price is a decreasing function of consumption channel preference, where the manufacturer’s wholesale price  $\omega^{N^*}$  decreasing and the channel preference  $\theta$  increasing. The manufacturer’s direct sales price is a decreasing function of consumption channel preference, where the manufacturer’s direct sales price  $P_m^{N^*}$  decreasing and channel preference increasing. The retailer’s price is an increasing function of consumption channel preference, where the retailer’s retail price  $P_r^{N^*}$  increasing and the channel preference  $\theta$  increasing. □

**Corollary 5.** In the NG pricing model, the retailer’s retail price is the same as the manufacturer’s direct sales price. When  $\bar{\theta} = \frac{2\beta^3 H + \gamma \beta \alpha}{2\beta^3 \alpha - 2\beta^2 \alpha + \gamma \beta \alpha}$  then  $P_m^{N^*} = P_r^{N^*}$  exists.

$$\text{Here, } H = \frac{\beta^2 \gamma c_m + \gamma^2 [G(\beta - \gamma) - \beta c_m] + \gamma \beta^2 B (\gamma - \beta)}{2\beta^3} (\beta - \gamma).$$

### 5. Numerical Analysis

In this section, numerical simulations performed to find out the influence of respective parameters. As the CLSC involving more complex recycling, so the merits of the decisions differ based on different scenarios. This paper uses numerical examples to see the differences in benefits based on different model decisions. In this CLSC, both the manufacturer and the retailer are rational decision-makers and making decisions based on their own best interests. To simplify the model, for analysis and to consider the scientific nature of the study, a certain type of digital products is selected as the object of study. The market is assumed to be a certain region where the recycling value is high to easily protect the environment.

Table 3 showed the simulation parameters values. Here,  $\varepsilon = [0, 0.6]$  and the profitability of cross-channel recycling is much lower than that of normal recycling of second-hand sales.

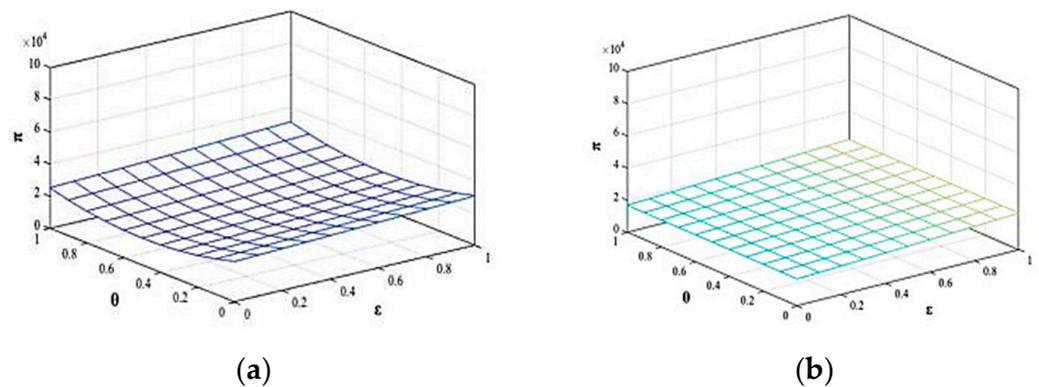
**Table 3.** Simulation parameters are assigned in the numerical study.

Parameter	$\alpha$	$k_r$	$k_m$	$\theta$	$\beta$	$\gamma$	$\bar{\omega}$	$c_m$	$t$	$s$	$h_r$	$h_m$	$h_{rm}$
Values	1000	0.2	0.1	(0.4, 0.6)	10	5	8	20	15	10	2	4	2

5.1. Comparison of Total Supply Chain Profits under Different Decision Models

Different channel recovery rates and consumption preferences have an impact on the overall profitability of the CLSC. The trend of total profitability in CLSC varies by channel recovery rate and consumption preference under different decision models.

Figure 2a,b represent the total profit of CLSC under centralised decision using differential and uniform pricing strategy, respectively. Under differential pricing strategy, the CLSC has the lowest costs and higher profits; however, in reality, it is difficult to achieve under centralised decision-making. The uniform pricing deviates from the principle of market competition under a centralised decision-making strategy. It is not conducive to some extent to retailer autonomy and motivation. Therefore, this approach rarely adopts in supply chains.



**Figure 2.** Total profit under (a) differential pricing and (b) uniform pricing.

It is reported from Figure 2a,b that when the value of  $\theta$  remains the same, the total profit increases with cross-channel  $\epsilon$ . This indicates that the increase in cross-channel recycling rate is conducive to reducing supply chain costs and improving recycling channels. The total profit is increasing in differential pricing, which is affected by channel preferences  $\theta$  rising. When channel preference  $\theta$  value in the middle, the total profit of the CLSC is relatively low. However, when the channel preference  $\theta$  value at high or low, the profit of the CLSC is relatively high. In contrast, total profit under uniform pricing is not affected by channel preference  $\theta$ , as there is no price elasticity and no cross-price sensitivity.

Figure 3a–c show the trends in total profits in the CLSC under the MLSG, the RLSG and the NG, respectively, under decentralised decision-making.

As per Figure 3a, in the MLSG model, when the value  $\theta$  remain constant, the total profit decreases as the cross-channel recycling rate  $\epsilon$  increases, which indicates that the raise of  $\epsilon$  increases recycling costs and has a negative impact on total supply chain profit. When the channel preference  $\theta$  is lower and  $\epsilon$  remain constant, then more consumers prefer the manufacturer’s online channel, which leads to total profit higher in the supply chain. Due to this scenario, the manufacturer is in a dominant position and its sales channels form a monopoly by the absence of competition in the market. As a result, overall product selling prices increase which maximizing total profits but consumers are often at a disadvantage situation.

As per Figure 3b, in the RLSG model, when  $\theta$  remain constant, the total profit increases as the cross-channel recovery rate  $\epsilon$  increases, which suggests that a raise in  $\epsilon$  helps to reduce the supply chain costs. When  $\epsilon$  remain constant and channel preference  $\theta$  value is at an intermediate, then the total profit of the CLSC is relatively low. However, when

channel preference  $\theta$  value at a high or low, then the profit of the CLSC is relatively high. This suggests that the total profit of CLSC is relatively higher when consumers prefer to buy from the retailer’s physical shop or the manufacturer’s online shop.

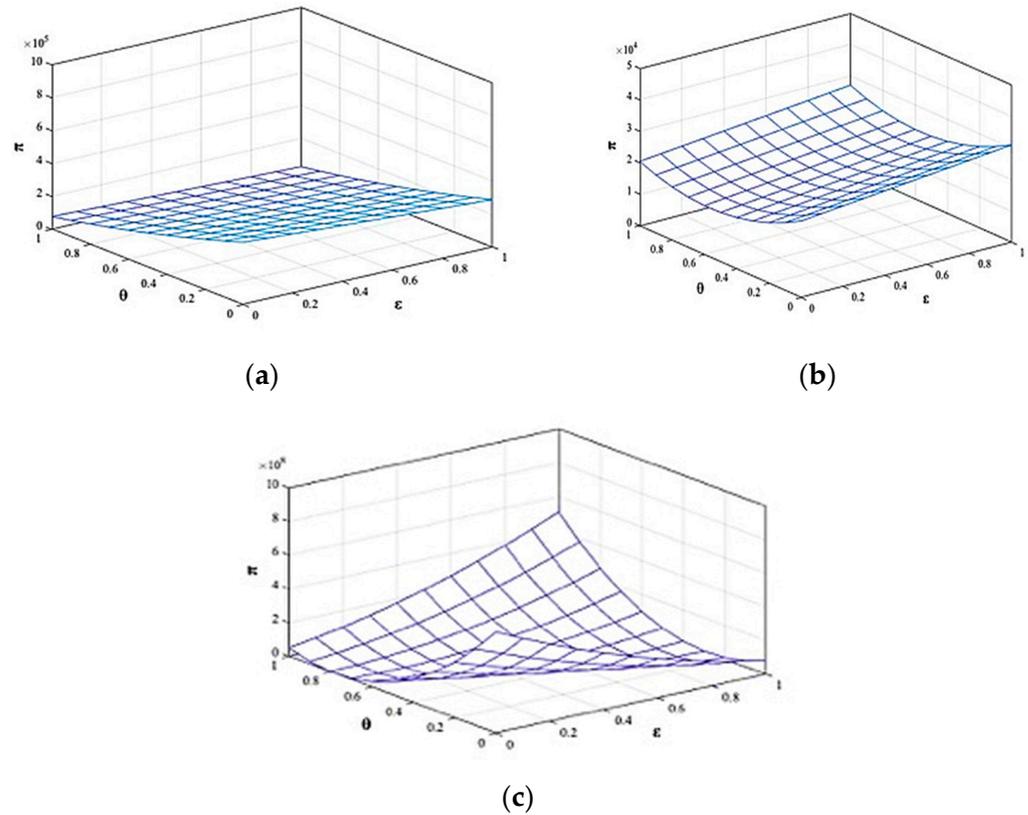


Figure 3. Total profit: (a) Manufacturer-led, (b) Retailer-led total profit and (c) Nash balanced.

As per Figure 3c, in the NG model, the total profit of the CLSC is maximised when both cross-channel recovery rates  $\epsilon$  and channel preferences  $\theta$  are either higher or lower. If the consumers prefer to buy the product via the manufacturer’s online channel then the total profit became higher due to the lower cross-channel recovery rate. Similarly, when consumer prefers to buy the product via the retailer’s channel then the total profit became higher due to higher cross-channel recovery rate. Here, both the manufacturer and the retailer are in an equal leading position for pricing decision making. In this model, both the manufacturer and the retailer prefer to sell more products using their consumer channel in terms of profit gain. This approach reduces recycling costs, and therefore, increase in their profit as well as overall profit.

5.2. Comparison of Pricing under Different Decision-Making Models

There are different pricing strategies under different decision-making models in the supply chain. Both higher and lower cross-channel recovery rates and channel preference influence the pricing strategies choices.

The comparison of pricing in the centralised decision-making model is shown in Figure 4. Here, low consumption channel preference  $\theta$  expressed by Figure 4a and high consumption channel preference  $\theta$  expressed by Figure 4b. Under differential pricing, manufacturer pricing  $P_m^C$  decreases with higher or lower  $\epsilon$  for flat  $P^U$ . However, whether channel consumption preferences  $\theta$  are high or low, the retailer pricing  $P_r^C$  is less affected by  $\epsilon$  under differential pricing.

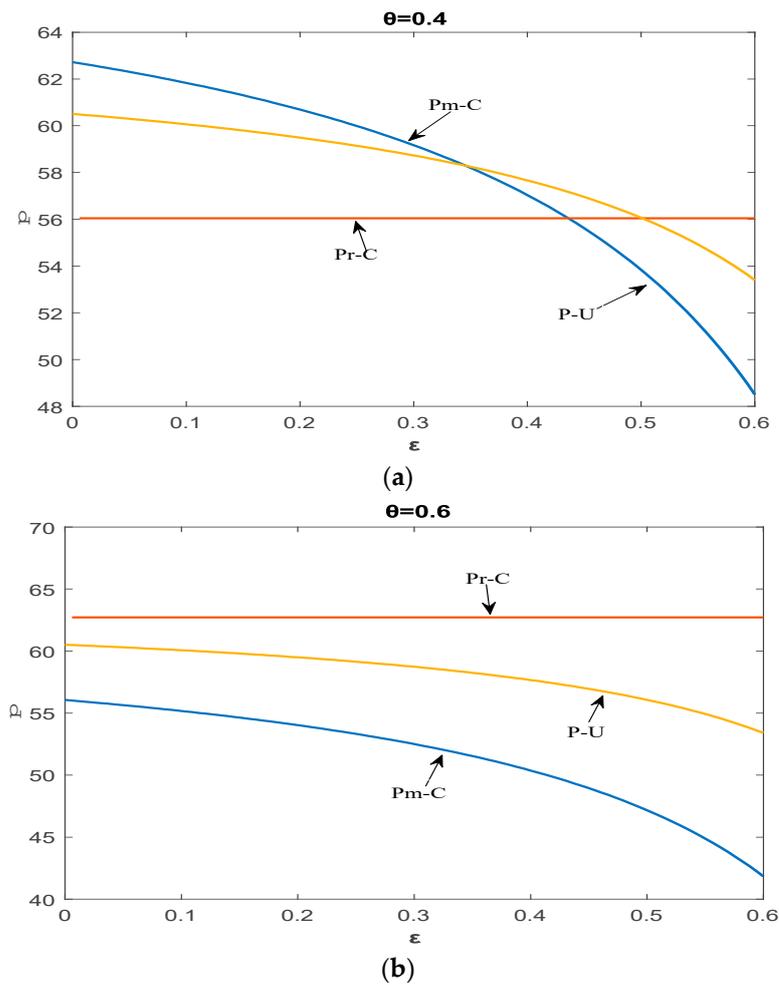
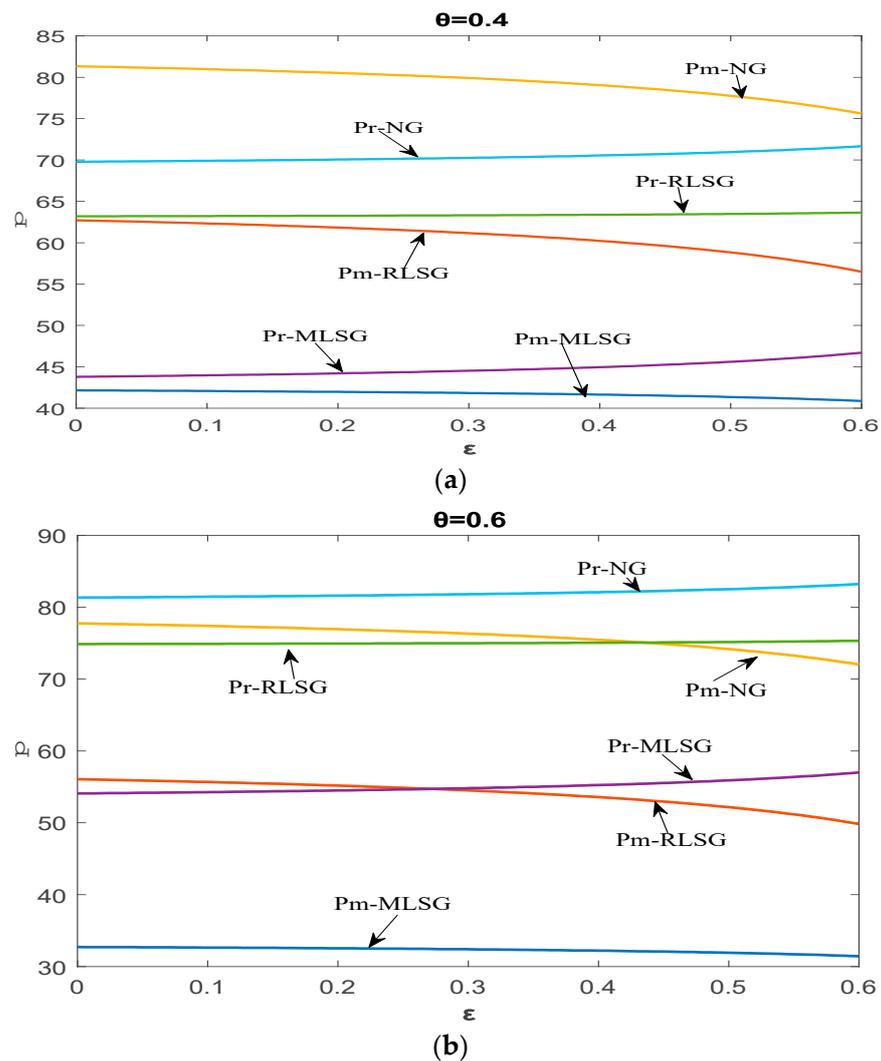


Figure 4. Comparison of pricing in a centralised decision-making model: (a) low consumption channel preference  $\theta$  and (b) high consumption channel preference  $\theta$ .

As per Figure 4a, in low consumption channel preference, the magnitude of pricing varies, when  $\epsilon$  is low then  $P_m^C > P^U > P_r^C$  and when  $\epsilon$  is high then  $P_r^C > P^U > P_m^C$ . In the high consumption channel preference  $\theta$  as expressed Figure 4b, there found  $P_r^C > P^U > P_m^C$  regardless of  $\epsilon$  whether is high or low. Under the centralised decision-making, it is reported that the cross-channel recovery rate  $\epsilon$  increases lead the consumer to a favourable position in the CLSC to reduce product pricing.

In the decentralised decision model, as shown in Figure 5a, whether the channel consumption preferences  $\theta$  are high or low, under manufacturer-led, retailer-led and Nash equilibrium the retailer pricing  $P_r^{MLSG}$ ,  $P_r^{RLSG}$  and  $P_r^{NG}$  all increase as cross-channel recovery rate  $\epsilon$  increases, at a specific point  $P_r^{MLSG} < P_r^{RLSG} < P_r^{NG}$ . Conversely as shown in Figure 5b, under manufacturer-led, retailer-led and Nash equilibrium the manufacturer pricing  $P_m^{MLSG}$ ,  $P_m^{RLSG}$  and  $P_m^{NG}$  all decrease as cross-channel recovery rate  $\epsilon$  increases, at a specific point  $P_m^{MLSG} < P_m^{RLSG} < P_m^{NG}$ .

Retailer and manufacturer pricing is highest in Nash equilibrium under decentralised decision-making. Similarly, retailer and manufacturer pricing are lowest under manufacturer-led and retailer-led decentralised decision-making. Regardless of channel preference  $\theta$  is high or low, both manufacturer-led and retailer-led, retailer pricing is higher than manufacturer pricing with  $P_m^{MLSG} < P_r^{MLSG}$  and  $P_m^{RLSG} < P_r^{RLSG}$ . Under Nash equilibrium decision, when channel preference is low, manufacturer pricing is higher than retailer pricing as  $P_r^{NG} < P_m^{NG}$ . Similarly, when channel preference is high, retailer retail pricing is higher than manufacturer pricing as  $P_m^{NG} < P_r^{NG}$ .



**Figure 5.** Comparison of pricing under decentralised decision-making models: (a) low consumption channel preference  $\theta$  and (b) high consumption channel preference  $\theta$ .

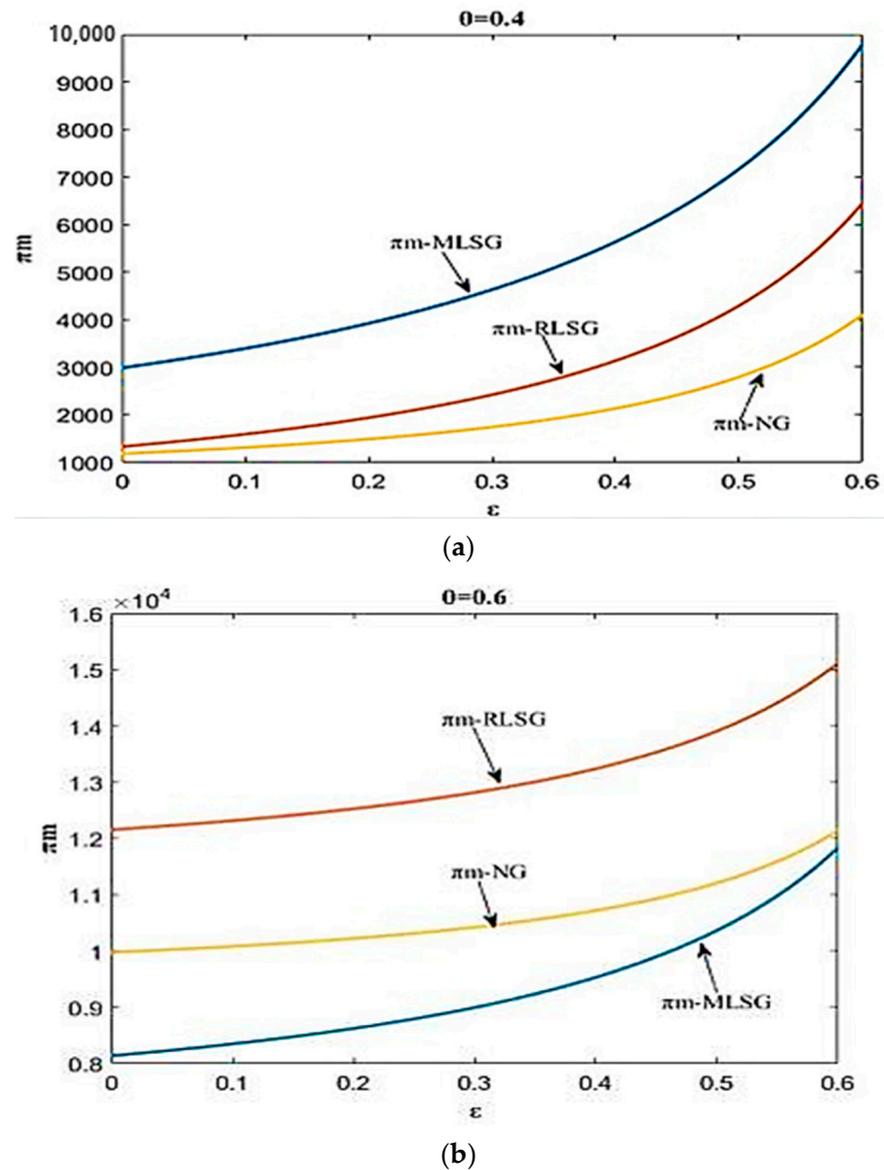
### 5.3. Comparison of Profits under Different Decision-Making Models

The profitability of the supply chain varies across different decision models. Both the level of channel preference and the cross-channel recovery rates influence profitability. In centralised decision-making, the result is a win-win partnership between manufacturers and retailers. The profits allocated according to their costs, neither profitability affects the decision-making choices. In contrast, under decentralised decision-making, has a stronger autonomy to choose and the tendency of profitability leads to choose the decision model that is most beneficial to them.

For the manufacturer pricing decision options, in the low consumption channel preference  $\theta$  showed in Figure 6a. The manufacturer’s profit size is preferred in the manufacturer-led model followed by the retailer-led model and then Nash equilibrium model as  $\pi_m^{MLSG} > \pi_m^{RLSG} > \pi_m^{NG}$ . In the high consumption channel preference model shown in Figure 6b. The manufacturer’s profit size is preferred in the retailer-led model followed by the Nash equilibrium model and then the manufacturer-led model as  $\pi_m^{RLSG} > \pi_m^{NG} > \pi_m^{MLSG}$ .

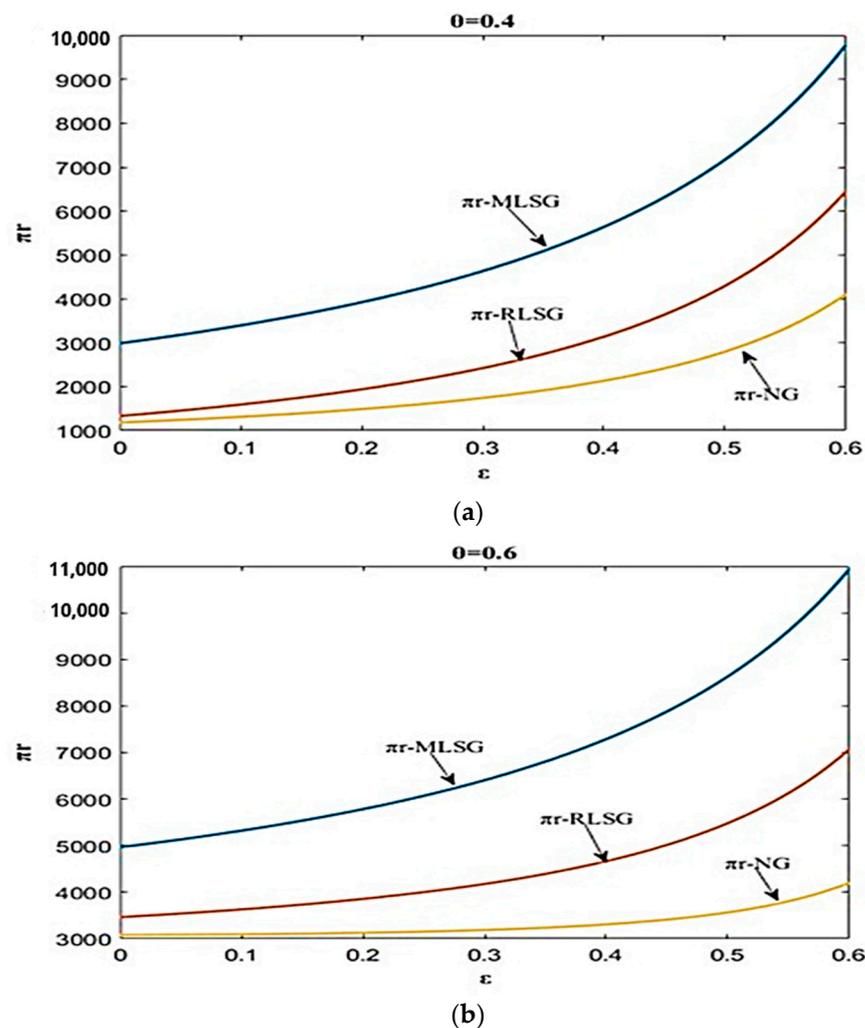
As shown in Figure 6, the manufacturer’s profitability increases with the increase of the cross-channel recovery  $\epsilon$  rate, which indicates that the manufacturer wants to increase the profitability by further increasing the cross-channel recovery rate  $\epsilon$  in different decision modes. At the same time, when the channel preference is  $\theta$  low, the manufacturer will

dominate by itself to obtain more profit. However, when the channel preference  $\theta$  is high, the manufacturer prefers retailer domination to reduce the cost of sales through its distribution system. The benefits can be gained by reducing the cost of sales through their distribution system.



**Figure 6.** A decentralised decision model for the manufacturer pricing decision options: (a) Low consumption channel preference  $\theta$  and (b) high consumption channel preference  $\theta$ .

For the retailer pricing decision options, whether the consumer channel preference  $\theta$  is high or low, the size of the retailer's profit is preferred the manufacturer-led model followed by the retailer-led model and then the Nash equilibrium model as  $\pi_m^{MLSG} > \pi_m^{RLSG} > \pi_m^{NG}$ . Moreover, this rule is the same for all decision models as per Figure 7a,b. As shown in Figure 7, the retailer's preference for the manufacturer-led model increases the retailer's profit as the cross-channel recycling rate  $\epsilon$  increases. This is suggesting that the retailer also wants the manufacturer to dominate the supply chain decision to reduce the cost of recycling by increasing the cross-channel recycling rate  $\epsilon$ , thereby generating a profit spillover through the scale effect of manufacturer recycling.



**Figure 7.** A decentralised decision model for retailer pricing decision options: (a) low consumption channel preference  $\theta$  and (b) high consumption channel preference  $\theta$ .

## 6. Conclusions and Future Work

This paper analyses the pricing and profitability of CLSCs through centralised and decentralised decision-making approaches. This study evaluated the impact of cross-channel recovery rates and consumer channel preferences to analyses retailer and manufacturer decision choices. Five types of decisions models such as differential pricing, uniform pricing, manufacturer-led, retailer-led and Nash equilibrium are used in this CLSC. The numerical examples show that the decision choices of retailers and manufacturers in CLSCs are not always the same across different decision models. The results of the analysis show that the impact of consumer channel preferences and cross-channel recovery rates on the CLSC varies across the different decision models. The main findings of the study are.

- (1). Under centralised decision-making, the total profit of the CLSC under differential pricing is higher than that under uniform pricing. Channel preference and cross-channel recovery rates have a greater impact on the pricing decisions of manufacturers and retailers. Under the differential pricing strategy, regardless of the channel preference, the manufacturer's pricing decreases if the cross-channel recovery rate increases. However, when the retailer's pricing is less affected by the cross-channel recovery rate then pricing remains at a stable level. The product pricing and the influence of consumer channel preference are weaker in uniform pricing. Moreover, product pricing decreases if the cross-channel recovery rate is low. As a result, price elasticity and cross-price sensitivity do not exist under a uniform pricing strategy.

- (2). Under decentralised decision-making, the trend of the total profit of the supply chain varies under different decision-making models. Here, cross-channel recovery rate and channel preference have a significant impact on the total profit. When the channel consumption preference is constant, the retailer's pricing increases if the cross-channel recovery rate increase. The manufacturer's pricing decreases if the cross-channel recovery rate increase. Firstly, retailer and manufacturer pricing are highest in Nash equilibrium. Secondly, retailer and manufacturer pricing are mid-level under retailer dominance. However, retailer and manufacturer pricing are lowest under manufacturer dominance. In addition, under low channel preference, manufacturers and retailers prefer to have the manufacturer dominate the decision. Similarly, under high channel preference, both manufacturers and retailers prefer to have others dominate model to achieve greater profitability for themselves.

The above analysis shows that the decision model chosen by the CLSC has a significant impact on profitability and pricing by channel preferences and different cross-channel recovery rates. Therefore, retailers and manufacturers need to choose the best decision model according to their actual situation. They also need to continue improving the optimisation conditions to enhance their competitiveness to gain greater profitability.

In the future, this CLSC can be further expanded to a competitive multi-channel CLSC with multiple manufacturers and multiple retailers. Moreover, a third-party recycling agency can be introduced to study the decision-making problem of a dual-channel CLSC with uncertain market demand through the design of a mixed recycling channel. This type of in-depth study on the supply chain decision-making problem will be created stronger theoretical and practical significance.

**Author Contributions:** Conceptualization, W.P. and M.L.; methodology, W.P.; software, W.P.; validation, W.P. and M.L.; formal analysis, W.P.; investigation, M.L.; resources, M.L.; data curation, W.P.; writing—original draft preparation, W.P.; writing—review and editing, W.P. and M.L.; visualization, M.L.; supervision, W.P.; project administration, W.P.; funding acquisition, W.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The author would like to thank the authors for the reference materials.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Nomenclature

CLSC	Closed-Loop Supply Chain
MLSG	Manufacturer-Led Stackelberg Game
RLSG	Retailer-Led Stackelberg Game
NG	Nash Equilibrium Game Pricing

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