

# **Reverse Logistics Pricing Strategy for a Green Supply Chain: A View of Customers' Environmental Awareness**

## ***Highlights***

- Reverse logistics of a green supply chain with environmentally-conscious customers is addressed.
- Customer word-of-mouth effect is taken into account.
- Two different pricing strategies and three game theoretic models have been derived and compared.
- Results indicate customer environmental awareness has positive effects on revenues.

## ***Abstract***

The effectiveness of a reverse logistics strategy is contingent upon the successful execution of activities related to materials and product reuse. Green supply chain (GSC) in reverse logistics aims to minimize byproducts from ending up in landfills. This paper considers a retailer responsible for recycling and a manufacturer responsible for remanufacturing. Customer environmental awareness (CEA) is operationalized as customer word-of-mouth effect. We form three game theoretic models for two different scenarios with different pricing strategies, i.e. a non-cooperative pricing scenario based on Stackelberg equilibrium and Nash equilibrium, and a joint pricing scenario within a cooperative game model. The paper suggests that stakeholders are better off making their pricing and manufacturing decision in cooperation.

**Keywords:** Green supply chain, Reverse logistics pricing strategy, Customer environmental awareness, Stackelberg equilibrium, Nash equilibrium, Cooperative game.

## **1. Introduction**

Enterprises are increasingly favoring investment in a greener SC specifically targeting on reverse logistics activities. Green supply chain management (GSCM) aims to achieve a win-win situation, balancing the tradeoffs between profit and environmental sustainability (Cucchiella et al., 2014; Dubey et al., 2018; Genovese et al., 2017, 2013; Govindan et al., 2015; Koh et al., 2013; Sarkis et al., 2011; Zhu et al., 2008; Zhu and Sarkis, 2004) This balancing act requires a series of management strategies which promote socially sustainable development through environmental protection and optimal use of resources (Katiyar et al., 2018). The demand for ‘green branding’ which was driven initially by environmental regulation and legislation, has triggered the adoption of green techniques in various supply chain management activities including product conceptualization and design, materials procurement, production, packaging and distribution, as well as end-of-life management of the product (Barari et al., 2012).

Reverse logistics and green product design are GSCM practices that demonstrate the firm’s commitment to environmental sustainability (Khor and Udin, 2013; Singhry, 2015). Green products are designed to reduce energy consumption, use fewer natural resources, increase the ratio of recycled materials, and reduce or eliminate toxic substances which are harmful to both the environment and human well being (Wee et al., 2011).

Researchers show a link between environmentally conscious consumers and design of green products (Beamon, 1999; Jayaram and Avittathur, 2015). Enterprises producing green products intend to project a perception of a strong sense of environmental responsibility which is expected to increase demand. Therefore, many enterprises regard strategies for producing green products as important policy to

improve competitiveness, establish a green corporate image, and achieve sustainable development.

One “greening” strategy involves activities related to re-using of materials collected via the reverse logistics chain. The aims are mainly to reduce consumption of materials, and reduce total production costs, and thus, increase economic profit to a certain acceptable level. For example, Kodak’s and Xerox’s implementation of reverse logistics reduced costs and earned them huge gains (Choudhary et al., 2015; Pishvae et al., 2010) while providing ‘environmentally sound’ products within a triple bottom line (TBL) framework (Zhao et al., 2012).

Customers’ increasing environmental awareness is making them more aware of the recycling of used products, and this is altering remanufacturing process perspectives. In short, customers more dedicated to and aware of “going green” can compel enterprises to increase their recovery efforts. Instead of recycling efforts being an afterthought, companies increasingly are becoming preemptive and designing increasingly modular products allowing greater materials recovery in the reverse logistics process. This applies especially to electronic products where the cost of removing the electronic components tends to outweigh the cost of replacing the circuits. Hence, even the plastic content of the casings are designed for easy removal.

The coordination among stakeholders is the key to the success of the green supply chain management, with game theory as the most popular methodology (c.f.-Azevedo et al., 2011; Barari et al., 2012; Chen et al., 2010; Chen and Sheu, 2009; Guide et al., 2000). For example, Maiti and Giri (2017) proposed decentralized (Nash game), manufacture-led and retailer-led Stackelberg games, and centralized (cooperative game) structures to analyze the two-way product recovery in a two-echelon closed-loop supply chain. In terms of reverse logistics pricing strategy, there is a

growing body of literature in green supply chain. Among the perspectives covered are the pricing of the used products (He, 2015) and refurbished/remanufactured products (Gan et al., 2017; Yoo and Kim, 2016). Here, reverse logistics pricing strategy involves maximizing the amount of recycling while keeping the price of recycling constant or achieving a lower price, while expanding the scale of remanufacturing. The objective is to capitalize on CEA to obtain a larger product market share.

In this paper, we model a case of reverse logistics in a two-tier SC between a manufacturer-retailer serving an environmentally conscious customer. The novelty of our paper is that it proposes an index to measure the degree of environmental consciousness of customers to counterbalance the tradeoff between maximizing the profit from reverse logistics, and obtaining an optimal price in the case that retailers take responsibility for recovery and manufacturers take responsibility for remanufacturing. The paper is organized as follows: section 2 is a brief review of existing work in this area, and section 3 models the GSC's revenue function taking account of each stakeholder's decision strategy. Section 4 introduces the environmentally conscious customer, and pricing strategies for the reverse logistics scenarios. Section 5 discusses some of the analytical results and simulations, and offers some insights for managers. Section 6 concludes the study with some recommendations for future research.

## **2. Literature review**

The literature related to this study can be grouped under work on customers' environmental awareness (CEA) and satisfaction, and reverse logistics and remanufacturing SC concepts:

### **2.1 CEA**

Building an environmentally friendly product is seen largely as involving a trade off with other features, particularly costs. There are two main ways to resolve the environmental dilemma, one depends on technological innovation to allow greater recovery of materials or a more efficient manufacturing process; the other seeks to capitalize on consumers' choices when greater environmental awareness leads to greater demand for eco-friendly purchases (Chan and Lau, 2002; Mainieri et al., 1997). Companies adopting the latter strategy either hope that customers will be willing to pay a premium for a green product, or are worried about consumers' unwillingness to purchase products that appear harmful to the environment (Mohd Suki, 2015).

In China, environmental education programs and environmental campaigns at different levels have given exposure to environmental awareness (Wong, 2010). However, there has been less emphasis on the interactions among the various stakeholders within the SC, and how they affect the relationship between green awareness and product sales. For example, Chen (2010) proposed a Nash equilibrium model for SC coordination with environmentally-conscious and price-sensitive customers; other studies look at product preferences and their effects on the carbon footprint (Du et al., 2015), environmentally sensitive customers (Altmann, 2015), and environmentally aware consumers (Giri and Bardhan, 2016). Zhang et al. (2013) applies game theory to a three-level SC system in which market demand correlates to the product's "greenness", and Xu and Xie (2016) took the impact of products' eco-friendly level on demand and constructed a two-stage closed-loop supply chain composed by a single manufacturer and a single retailer. Ghosh and Shah (2012) build game theoretic models to show how greening levels, prices, and profits are influenced by channel structures.

## **2.2 Reverse logistics and remanufacturing in the green supply chain**

The complexity of the GSC has increased from being an open-loop SC to being a closed-loop SC, from being a single SC to being a network SC, making the assumption of deterministic demand mostly infeasible. More research is required to investigate complex GSCs models with stochastic demand, dynamic rather than static networks, and asymmetric information (Keyvanshokoo et al., 2013; Lieckens and Vandaele, 2007; Niknejad and Petrovic, 2014; Pishvaei et al., 2011; Zhang et al., 2014). Based on environmental, legal, social, and economic factors, reverse logistics and closed-loop supply chain issues have attracted attention among both academia and practitioners (Govindan et al., 2015; Khor et al., 2016). Reverse logistics operations and closed-loop SCs account for the reverse flow of materials or value from the final consumer to the producer (Haddadsisakht and Ryan, 2018; Rowshannahad et al., 2018). This process can be modeled as a remanufacturing process, i.e. rebuilding products to the specifications of the original manufactured products, using a combination of reused, repaired, and new parts (Johnson and McCarthy, 2014).

The focus of reverse logistics could also include reducing energy use by creating a more efficient back-to-front process aimed at eliminating landfill of industrial products as much as possible (Guide Jr et al., 2000). Remanufacturing must not be confused with recycling. The former is responsible for the rebuilding/reusing of materials or components that have been recovered/recycled.

The value derived from remanufacturing is observed when the performance or the expected life of the new product is insured, or can be quantified for the remanufacturing process. In recent decades, many studies have been conducted on the optimal pricing decisions of stakeholders related to SCM, particularly reverse

logistics and remanufacturing.

We provide a brief review of this work, and especially studies dealing with the problem of pricing remanufactured products and recycled materials. Motivated by the real case of a company involved in the acquisition and remanufacture of used cell phones, Nikolaidis (2009) proposes a simple mathematical programming model to decide about the quantities to be purchased, and the quantities to be remanufactured.

Based on two hypotheses related to the differential price of remanufactured products and new products, and differential price for recycling waste products, Zheng (2012) analyzes decentralized and centralized pricing models, and obtains an optimal pricing strategy for SC members. Xiong et al. (2014) propose a dynamic pricing policy for used products (cores) of uncertain quality. Chen (2016) proposes game models for different pricing strategies related to partial and direct reuse of scrapped automobiles recycled by a third-party recycler, and extend them to analyze the problem with a government subsidy for the third-party recycler.

However, considering isolated activities or processes does not provide a holistic view of the GSC with environmentally-conscious customers, reverse logistics, and remanufacturing. In the GSC context, remanufacturing provides the customer with an opportunity to acquire a product that meets the original product standards but at a lower price than a completely new product (Jayaraman et al., 1999), with the remanufacturing companies dependent on customers returning used products (Östlin et al., 2008). In the same way that the price of the product affects customer demand, the acquisition price for used products affects the willingness of customers to transfer products and affects the quantities recycled. Work on acquisition pricing of used products is scarce (Keyvanshokoo et al., 2013), and the few existing studies tend to focus on the manufacturer. For example, they examine how the acquisition efforts of

manufacturers directly influence the strictly increasing, concave, and continuous core collection yield function (Lechner and Reimann, 2014). However, there are other drivers, such as customer's environmental satisfaction, the effect on other customers of information being passed on about the buying experience, and the worker experience under learning and forgetting (Giri and Glock, 2017). Thus, the most important contribution of this paper is that it investigates the impact of environmentally-conscious customers and the word-of-mouth effect on the supply of the recyclable product, the willingness to transfer the used product, and the quantity recycled. This paper also discusses revenues and reverse logistics price changes according to the changes in key parameters which ultimately affect the reverse logistics pricing and the decisions of each stakeholder.

### **3. Problem context**

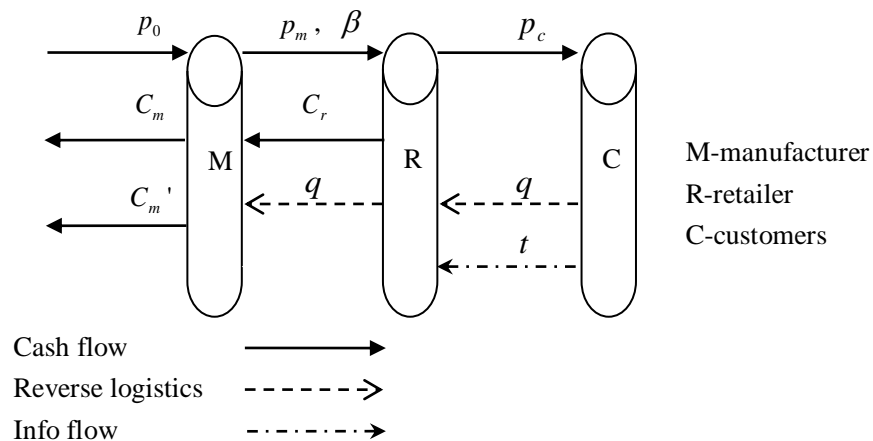
#### ***3.1 Description of the green supply chain system***

Figure 1 depicts a GSC with a manufacturer, a retailer, and environmentally aware customers (Gu et al., 2005). In this system, the GSC recycles the products supplied in the market. The retailer is responsible for recycling used products from customers, the manufacturer obtains those recycled products from the retailer at a certain price, then remanufactures them, and sells the remanufactured products at the same price as a brand new product, i.e. there is no difference in the price of the remanufactured product and the newly-manufactured product.

The retailer evaluates the performance of the products before recycling. This guarantees that the recycled products can be fully reused by the manufacturer, and makes the manufacturer's production costs lower for the remanufactured products. In order to encourage the retailer to recycle the product, the manufacture pays the retailer



at the price of  $p_m$  which is higher than price the retailer pays to the customer  $p_c$ , representing a marginal profit rate of  $\beta$ . As already mentioned, the increase in customers' environmental satisfaction is caused by the enterprises' green recycling practice, and can induce customers' to buy more products and to recycle more products. We assume sufficient market demand.



**Figure 1.** Green supply chain system with a manufacturer, a retailer and environmentally-conscious customers

The notations used in the rest of the paper are listed below:

- **Sets**

$F$  Set of reverse logistics pricing decision strategies of the GCS;

- **Parameters**

$p_0$  The final selling price of manufactured products;

$p_c$  The recycling price that the retailer pays to the customers;

$t$  The fluctuation ratio of the CEA with the word-of-mouth effect,  $0 < t < 1$ ;

$n$  The number of customers in the GSC system;

$s$  The total CEA of the GSC system;

$C_m$  The unit marginal production cost of remanufactured products;

- $C_r$  The unit operating cost of retailers;
- $q^0$  The supply of recyclable product without the impact of CEA;
- $q$  The supply of recyclable product with the impact of CEA;
- $d$  The conversion coefficient of the recyclable products;
- $k$  The price elasticity coefficient of the recyclable products;
- $\Pi_m$  The manufacturer's revenue;
- $\Pi_r$  The retailer's revenue;
- $\Pi$  The revenue from the reverse logistics system;

• **Variables**

- $p_m$  The recycling price that the manufacturer pays to the retailer;
- $\beta$  The marginal profit rate that the retailer accepts based on the manufacturer's commitment to recycle the items.

### 3.2 Assumptions

#### 3.2.1 Customer's environmental awareness and the word-of-mouth effect

We consider the situation where one customer (the first person) is satisfied with the product he has purchased and passes on this information to another customer (the second person). It is most likely that the second person will choose to buy the same product as a result of the word-of-mouth effect (Ajlou et al., 2016; Hervas-Drane, 2015; Peluso et al., 2017). In this case, we assume that the recycling and remanufacturing efforts of enterprises increase customers' environmental awareness and stimulate customers to buy more remanufactured products. Here, recycling and remanufacturing practices can be viewed as a special kind of service to satisfy customers' psychological requirement for protection of the environment. The resulting customer psychological effect caused by this service is called CEA. The

CEA can be used to measure the degree of satisfaction of customers psychological requirement for protection of the environment, and the increased supply of recyclable products resulting.

Hereafter, we denote the fluctuation ratio of customers' environmental awareness with the word-of-mouth effect as  $t$ , where  $0 < t < 1$ , and the total CEA in the GSC system as  $s$ , which is a function of  $t$ . Suppose that the initial CEA of the first person is 1, then the second person's CEA will be  $t$ , and the total CEA of the GSC system is an infinite sequence  $(t^n)_{n=1}^{\infty} = (1, t, t^2, \dots)$ , with the sum of this infinite series  $\frac{1-t^{n+1}}{1-t}$ , i.e. the GSC's CEA is  $s(t) = \frac{1-t^{n+1}}{1-t}$ . To simplify the analysis, suppose that the number of customers is sufficiently large, i.e.  $n \rightarrow \infty$ , then the total CEA of the GSC system can be written as  $s(t) = \frac{1}{1-t}$ .

### 3.2.2 Supply of recyclable product

As mentioned in the literature review (c.f. Zheng, 2012; Xiong et al., 2014; Chen, 2016), the reverse logistics pricing strategy will affect the supply of recyclable products and the demand for manufactured products and remanufactured products.

Recycling markets are controlled by the same laws of supply and demand that control other markets. In the case of supply of recyclable products, we assume here that it is determined mainly by the recycling price that the retailer pays to customers (denoted  $p_c$ ). We investigated the shape of the supply curves for the normal product and the recyclable product. We found the curves for the recyclable product are more fitted to the exponential function, given a period of time and without considering other elements. Thus, the supply of recyclable product can be expressed as:

$$q^0 = f(p_c) = dp_c^k \quad (1)$$

where,  $k$  is the price elasticity coefficient of the recyclable products,  $d$  is the conversion coefficient, and  $k > 1, d > 0$  (Lau and Lau, 2003).

When the impact of CEA is considered, the final result of the supply of recyclable products can be expressed as :

$$q = s(t)q^0 = \frac{1}{1-t} dp_c^k = dp_c^k + \frac{t}{1-t} dp_c^k \quad (2)$$

where,  $\frac{t}{1-t} dp_c^k$  represents the increased supply due to the increase in CEA.

### 3.2.3 Manufacturer's and retailer's revenues and the reverse logistics system

As assumed above, the number of customers is sufficiently large, i.e.  $n \rightarrow \infty$  or the market of this GSC system would be unlimited, so the retail price is set by the retailer as a fixed price that is not subject to bargaining, and is denoted  $p_0$ .

The recycling price paid by the manufacturer to the retailer is denoted  $p_m$ , and is assumed to be related to  $p_c$ , and can be written as:

$$p_c = (1 - \beta) p_m \quad (3)$$

where  $\beta$  is the marginal profit rate that the retailer accepts based on the manufacturer's commitment to recycle the items, which is the decision variable of the retailer within  $0 \leq \beta \leq 1$ .

In this paper, the revenue of the stakeholders in the GCS is limited to the reverse logistics, i.e. the revenue of the manufacturer is a composite of the recycling costs and the production costs of the recyclable products, and the income from the sale of these products. The retailer's revenue is a composite of the cost of recycling and the income from selling the recycled products. Based on the above hypothesis and analysis, for given recycling prices of  $p_m$  and  $p_c$ , the manufacturer's revenue can be expressed

as:

$$\Pi_m = (p_0 - C_m - p_m) \frac{1}{1-t} dp_c^k = \frac{d}{1-t} (1-\beta)^k p_m^k (p_0 - C_m - p_m) \quad (4)$$

The retailer's revenue can be expressed as:

$$\Pi_r = (p_m - C_r - p_c) \frac{1}{1-t} dp_c^k = \frac{d}{1-t} (1-\beta)^k p_m^k (\beta p_m - C_r) \quad (5)$$

The revenue for the reverse logistics system can be expressed as:

$$\Pi = \Pi_m + \Pi_r = \frac{d}{1-t} (1-\beta)^k p_m^k [p_0 - C_r - C_m - (1-\beta)p_m] \quad (6)$$

### 3.4 Decision strategy in the reverse logistics system

Here, the solution of  $(p_m, \beta)$  is defined as a decision strategy of the reverse logistics system (i.e. the solution of the three game models discussed in the next section). In order to simplify the following analysis, *Lemma 1* is proposed as:

**Lemma 1:** When  $\frac{k-1}{k+1}(p_0 - C_m) \leq p_m \leq p_0 - C_m$ ,  $\frac{C_r}{p_m} \leq \beta \leq \frac{2p_m + C_r(k-1)}{p_m(k+1)}$ , 1)  $\Pi_m$  is a

concave function of  $p_m$ ; 2)  $\Pi_r$  is a concave function of  $\beta$ ; and 3)  $\Pi$  is a concave

function of  $(p_m, \beta)$ , as  $\frac{k}{k+1}(p_0 - C_m - C_r) < (1-\beta)p_m \leq p_0 - C_m - C_r$  is also satisfied.

*Lemma 1* indicates that only if  $(p_m, \beta) \in F$  holds, does the decision strategy cause a reverse for each stakeholder in the reverse logistics system, otherwise, there is no reverse for the stakeholders, or the reverse will decrease due to the decrease in the quantity recycled.

Then the set of decision strategies can be represented as follows:

$$F = \left\{ (p_m, \beta) \mid \frac{k-1}{k+1}(p_0 - C_m) \leq p_m \leq p_0 - C_m, \frac{C_r}{p_m} \leq \beta \leq \frac{2p_m + C_r(k-1)}{p_m(k+1)}, \frac{k}{k+1}(p_0 - C_m - C_r) < (1-\beta)p_m \leq p_0 - C_m - C_r \right\} \quad (7)$$

## 4. Game models for reverse logistics system with CEA

## 4.1 Non-cooperative pricing scenario

### 4.1.1 Stackelberg equilibrium (S-model)

In this model, the manufacturer and the retailer are part of a sequential non-cooperative game. In this game, the manufacturer plays a dominant role as the leader, and the retailer is the follower, i.e. this is a Stackelberg game model. In this game, the manufacturer sets the reverse logistics pricing decision based on market price information, and the retailer subsequently makes its own reverse logistics pricing decision after acknowledging the manufacturer's reverse logistics pricing decision. Following these decisions, the retailer recycles the used products from customers at a given price  $p_c$ , and the manufacturer buys the recycled products from the retailer at a given price  $p_m$ .

In figuring out the solutions to Stackelberg equilibrium equations, the aim is to acquire the corresponding function of the second stage. That is, the retailer pursues maximum revenue based on the information about the pricing decisions made by the manufacturer. According to **Lemma 1**,  $\Pi_r$  is a concave function of  $\beta$ , and, the optimal decision variable  $\beta^*$  can be derived by solving the first order condition of  $\Pi_r$  for the maximum revenue,  $\partial \Pi_r / \partial \beta = 0$ , i.e.

$$\frac{\partial \Pi_r}{\partial \beta} = \frac{d}{1-t} p_m^k (1-\beta)^{k-1} [p_m(1-\beta) - k(\beta p_m - C_r)] = 0$$

Then the optimal decision variable  $\beta^*$  can be written as:

$$\beta^* = \frac{p_m + kC_r}{p_m(1+k)} \quad (8)$$

Eq.(8) illustrates the optimal decision of the retailer when the recycling price  $p_m$  has been given by the manufacturer, i.e. the retailer should bargain over the optimal marginal profit rate offered by the manufacturer, and sets its recycling pricing  $p_c$  to

obtain the maximum revenue.

Put Eq.(8) into the revenue function of the manufacturer, i.e. Eq.(4), and the revenue function can be addressed as:

$$\Pi_m = \frac{d}{1-t} \left( \frac{k}{k+1} \right)^k (p_m - C_r)^k [p_0 - C_m - p_m] \quad (9)$$

According to **Lemma 1**,  $\Pi_m$  is a concave function of  $p_m$ , and the optimal decision variable  $p_m$  can be derived by solving the first order condition of  $\Pi_m$  for the maximum revenue,  $\partial \Pi_m / \partial p_m = 0$ , i.e.

$$\frac{\partial \Pi_m}{\partial p_m} = \frac{d}{1-t} \left( \frac{k}{k+1} \right)^k (p_m - C_r)^{k-1} \{k[p_0 - C_m - p_m] - p_m + C_r\} = 0$$

Then the optimal decision variable  $p_m^*$  can be written as:

$$p_m^* = \frac{k(p_0 - C_m) + C_r}{k+1} \quad (10)$$

and the solution to the *S-model* can be written as:

$$(p_m^*, \beta^*) = \left( \frac{k(p_0 - C_m) + C_r}{k+1}, \frac{1}{k+1} + \frac{kC_r}{k(p_0 - C_m) + C_r} \right) \quad (11)$$

Then, the revenues of the manufacturer, the retailer and the reverse logistics system can be written as:

$$\Pi_m^* = \frac{d}{1-t} \frac{k^{2k}}{(k+1)^{2k+1}} [p_0 - C_m - C_r]^{k+1} \quad (12)$$

$$\Pi_r^* = \frac{d}{1-t} \frac{k^{2k+1}}{(k+1)^{2k+2}} [p_0 - C_m - C_r]^{k+1} \quad (13)$$

$$\Pi^* = \frac{d}{1-t} \frac{(2k+1)k^{2k}}{(k+1)^{2k+2}} [p_0 - C_m - C_r]^{k+1} \quad (14)$$

#### 4.1.2 Nash equilibrium (N-model)

The rapid development of modern large retailers such as Wal-Mart and Carrefour, is bringing retailers closer to customers in the SC than manufacturers. The retailer plays

an increasingly important role especially in the reverse logistics system, and is an agent between the manufacturer and customers.

Given the increased status of the retailer in the SC, and in the context of reverse logistics, this paper assumes that neither the manufacturer nor the retailer is dominant; instead, they make decisions independently, impartially, and simultaneously within a static Nash game. The solution to this model is Nash equilibrium.

In this case, the problem is the maximum of the manufacturer's and the retailer's revenue.

The manufacturer's maximum revenue can be expressed as:

$$\begin{aligned} \max_{p_m} \Pi_m &= \frac{d}{1-t} (1-\beta)^k p_m^k (p_0 - C_m - p_m) \\ \text{s.t.} \quad &\frac{k-1}{k+1} (p_0 - C_m) \leq p_m \leq p_0 - C_m \end{aligned} \quad (15)$$

The retailer's maximum revenue can be expressed as:

$$\begin{aligned} \max_{\beta} \Pi_r &= \frac{d}{1-t} (1-\beta)^k p_m^k (\beta p_m - C_r) \\ \text{s.t.} \quad &\frac{C_r}{p_m} \leq \beta \leq \frac{2p_m + C_r(k-1)}{p_m(k+1)} \end{aligned} \quad (16)$$

The solution to the *N-model* is obtained from the following first order conditions:

$$\begin{cases} \frac{\partial \Pi_m}{\partial p_m} = \frac{d}{1-t} (1-\beta)^k p_m^{k-1} (kp_0 - kC_m - kp_m - p_m) \\ \frac{\partial \Pi_r}{\partial \beta} = \frac{d}{1-t} (1-\beta)^{k-1} p_m^k [p_m(1-\beta) - k(\beta p_m - C_r)] \end{cases}$$

The solution to the *N-model* can be written as:

$$(p_m^{**}, \beta^{**}) = \left( \frac{k}{k+1} (p_0 - C_m), \frac{1}{k+1} + \frac{C_r}{p_0 - C_m} \right) \quad (17)$$

Then, the revenues of the manufacturer, the retailer, and the reverse logistics system can be written as:

$$\Pi_m^{**} = \frac{d}{1-t} \frac{k^k}{(k+1)^{2k+1}} (p_0 - C_m)^k [k(p_0 - C_m - C_r) - C_r]^k \quad (18)$$



$$\Pi_r^{**} = \frac{d}{1-t} \frac{k^k}{(k+1)^{2k+2}} [k(p_0 - C_m - C_r) - C_r]^{k+1} \quad (19)$$

$$\Pi^{**} = \frac{d}{1-t} \frac{k^k}{(k+1)^{2k+2}} [k(p_0 - C_m - C_r) - C_r]^k [(k+1)(p_0 - C_m) + k(p_0 - C_m - C_r) - C_r] \quad (20)$$

#### 4.2 Joint pricing scenario (J-model)

The cooperation game model is the kind of game model in which players make decisions together to create a surplus of cooperation in a context of information-sharing, with the purpose of maximizing the total revenue of the reverse logistics system. In the reverse logistics system in this subsection, the manufacturer and the retailer make their decisions jointly. According to *Lemma 1*  $\Pi$  is a concave function of  $(p_m, \beta)$ , the model in this Joint pricing scenario becomes a double-variable optimization as follows:

$$\left\{ \begin{array}{l} \text{Max} \Pi = \frac{d}{1-t} (1-\beta)^k p_m^k [p_0 - C_r - C_m - (1-\beta)p_m] \\ \text{s.t.} \quad \frac{k-1}{k+1} (p_0 - C_m) \leq p_m \leq p_0 - C_m \\ \frac{C_r}{p_m} \leq \beta \leq \frac{2p_m + C_r(k-1)}{p_m(k+1)} \\ \frac{k}{k+1} (p_0 - C_m - C_r) < (1-\beta)p_m \leq p_0 - C_m - C_r \\ p_m > 0, 1 > \beta > 0, 1 > t > 0, k > 1 \end{array} \right. \quad (21)$$

The solution to the *J-model* can be obtained from the following first order condition:

$$\left\{ \begin{array}{l} \frac{\partial \Pi}{\partial p_m} = \frac{d}{1-t} (1-\beta)^k p_m^{k-1} [k(p_0 - C_m - C_r) - (1+k)(1-\beta)p_m] \\ \frac{\partial \Pi}{\partial \beta} = -\frac{d}{1-t} p_m^k (1-\beta)^{k-1} [k(p_0 - C_m - C_r) - (1+k)(1-\beta)p_m] \end{array} \right.$$

The solution to the *J-model* can be written as:

$$J = \left\{ (p_m^{***}, \beta^{***}) \mid (1-\beta^{***})p_m^{***} = \frac{k}{k+1} (p_0 - C_m - C_r), (p_m^{***}, \beta^{***}) \in F \right\} \quad (22)$$

Then, the revenue of the reverse logistics system can be expressed as:

$$\Pi^{***} = \frac{d}{1-t} \frac{k^k}{(k+1)^{k+1}} (p_0 - C_m - C_r)^{k+1} \quad (24)$$

## 5. Simulation case study

### 5.1 Typical model results

In this section, we propose a numerical example to illustrate some important characteristics of the above results. The main parameters are subjected to comprehensive sensitivity analysis to investigate the behavior of the models. Similar to previous literature in this area (Gan et al., 2017, 2015; Gönsch, 2015), the values of the parameters are as follows:

$$p_0 = 10, \quad C_m = 3.5, \quad C_r = 1, \quad d = 1000, \quad t = 0.8, \quad k = 2$$

Table 1 shows the results with above parameter values, including the revenues of the manufacturer, the retailer, and the reverse logistics system, the recycling price that the retailer pays to customers, and the quantity of recycled products.

It can be observed that the *J-model* yields the best results for the reverse logistic system revenue, the recycling price, and quantity of recycled material. The *S-model* shows a higher recycling price and higher quantity of recycled material, and higher system revenue compared to the *N-model*.

**Table 1** the results of the models in the simulation case

	Revenue (\$)			Recycling price of retailer (\$)	Quantity of recycled items
	Manufacturer	Retailer	System		
<i>S-model</i>	54774	36516	91290	2.444	29876
<i>N-model</i>	53498	27435	80933	2.222	24691
<i>J-model</i>			123240	3.667	67222

### 5.2 Managerial insights and sensitivity analyses

This section discusses the effects of changes in the model's main parameters on the revenues of the manufacturer, the retailer, and the reverse logistics system, the retailer's recycling price, and the quantity of recycled product. It analyzes the combined effect of multiple parameters.

### 5.2.1 The fluctuation ratio of the CEA ( $t$ )

In discussing the fluctuation ratio of the CEA ( $t$ ), the other parameters are the same as in section 5.1 with the exception of the fluctuation ratio of the CEA  $t \in (0,1)$ .

- **Insight 1** Revenue changes according to the fluctuation ratio variation

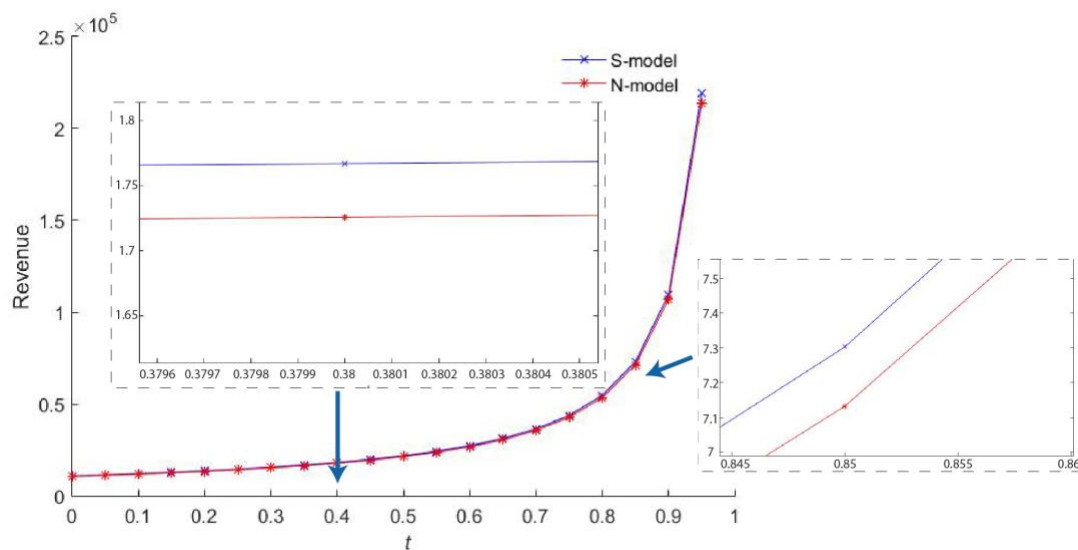
Graphs 1) and 2) in Figure 2 show the manufacturer's and the retailer's revenue changes. In both cases, these revenues increase with an increasing  $t$ . The manufacturer's and the retailer's revenues in the *S-model* are larger than in the *N-model* when  $t$  evolves from the start point, i.e.  $t = 0$ . Graph 3) in Figure 2 shows the changes to the revenue of the total reverse logistics system in the non-cooperative pricing scenario (*S-model* and *N-model*) and the joint pricing scenario (*J-model*). The total reverse logistics system revenue increases with an increasing  $t$ , and the relationship of the system revenue in these three models is: *J-model* > *S-model* > *N-model*. The results presented in Table 1 confirm this. It can be observed that raising the fluctuation ratio  $t$  encourages all the members of the SC to conduct greener production methods, to promote environmental awareness among customers, and to make decisions cooperatively to achieve a higher system revenue.

As customers' environmental consciousness increases, CEA will have a greater impact on the revenue of all SC members and the SC system, especially in this simulation case study when  $t > 0.8$ , and there are sharp increases in each curve. The stakeholders in the GSC should cooperate to make the product greener. If stakeholders

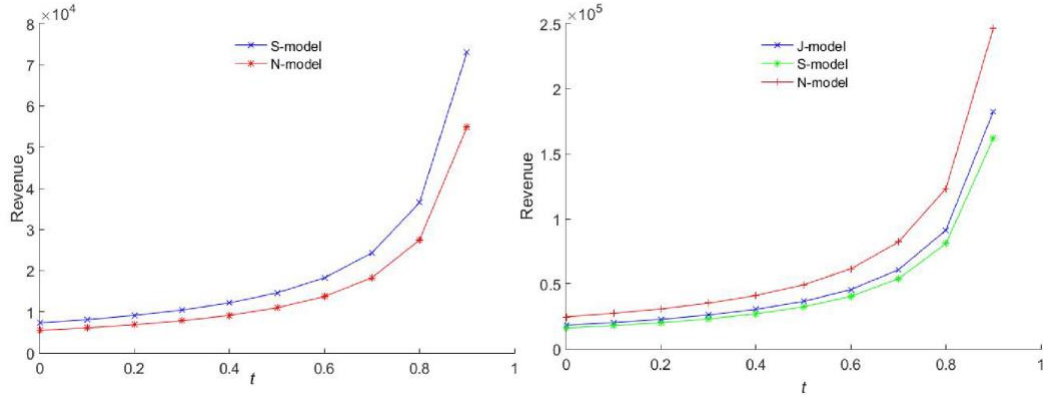
make their decisions independently, this will result in lower stakeholder revenue and lower system revenue.

- **Insight 2** Quantity of recycled material changes with the fluctuation ratio variation

Figure 3 shows that the quantity of recycled materials differ for the SC system in the two non-cooperative pricing and the joint pricing models. The quantity of recycled material increases with a rising  $t$ , and the relationship of this quantity in the three models is:  $J\text{-model} > S\text{-model} > N\text{-model}$ . The results presented in Table 1 confirm this indication.



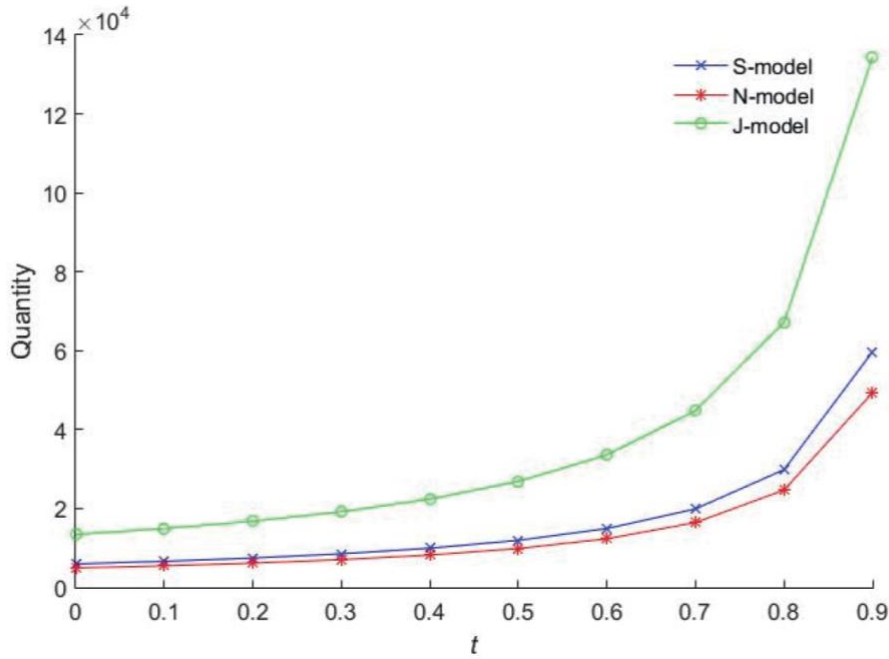
1) manufacturer



2) retailer

3) total reverse logistics system

**Figure 2.** Revenue changes according to the fluctuation ratio rising



**Figure 3.** Quantity of recycled material changes according to the increase in the fluctuation ratio

It can be seen that a rise in the fluctuation ratio  $t$  encourages more customers to sell used products to the retailer. The quantity of recycled products is higher if the SC members make their decisions cooperatively.

### 5.2.2 The price elasticity coefficient of the recycled products ( $k$ )

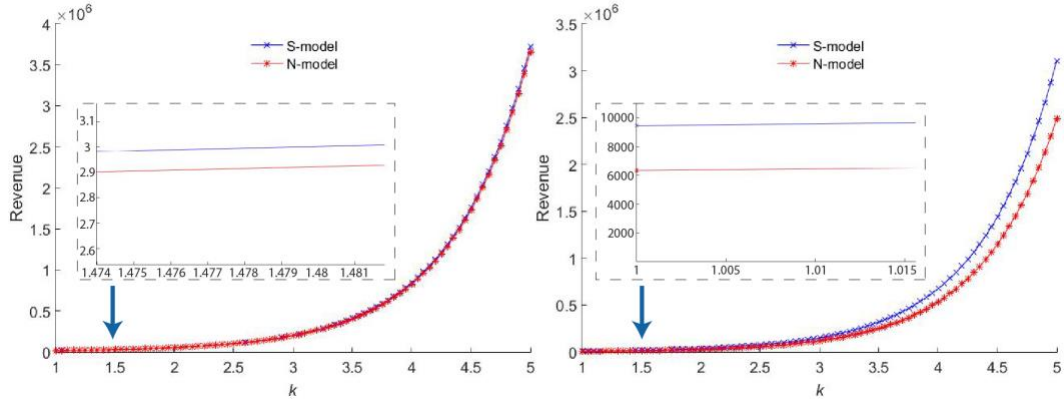
In the discussion of the price elasticity coefficient of the recycled products ( $k$ ), the

parameters are the same as those in section 5.1 with the exception of the price elasticity coefficient of the recycled products  $k \in (1,5)$ .

- **Insight 3** Revenue changes according to the price elasticity coefficient  $k$

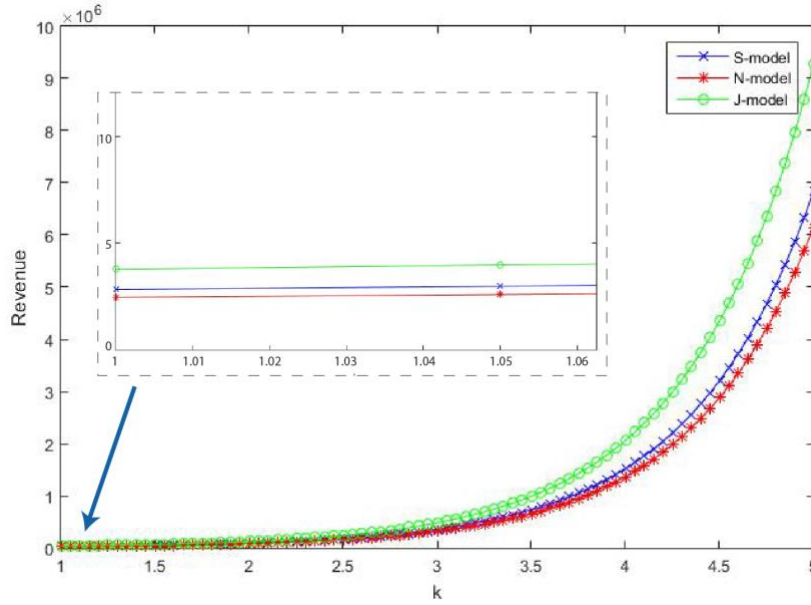
Graphs 1) and 2) in Figure 4 show the revenue changes for the manufacturer and the retailer in the non-cooperative pricing scenario (*S-model* and *N-model*). The revenues of the manufacturer and the retailer both increase with an increasing  $k$ . The manufacturer's and the retailer's revenues are larger in the *S-model* compared to *N-model* when  $k \in (1,5)$ . In Graph 3), the total reverse logistics system revenues in the *S-model* and *N-model* show the same changes as the manufacturer's and the retailer's revenues which increase with an increasing  $k$ . In the *J-model* in the joint pricing scenario, the total system revenue is always larger than in the other two models. It can be seen that raising the price elasticity coefficient  $k$  encourages all members of the SC to produce a more price sensitive product, to gain more revenue, and to make decisions cooperatively which is in line with Zhu et al. (2010).

As customers' become more price sensitive, improving the product's price elasticity coefficient  $k$  will have a greater impact on the revenues of all SC members and the system, especially in this simulation case study when  $k > 4$ , and there are sharp increases in each curve. The stakeholders in GSC should cooperate to make the product more price elastic. If stakeholders decide independently, this will result in lower stakeholder and system revenues.



1) manufacturer

2) retailer



3) total reverse logistics system

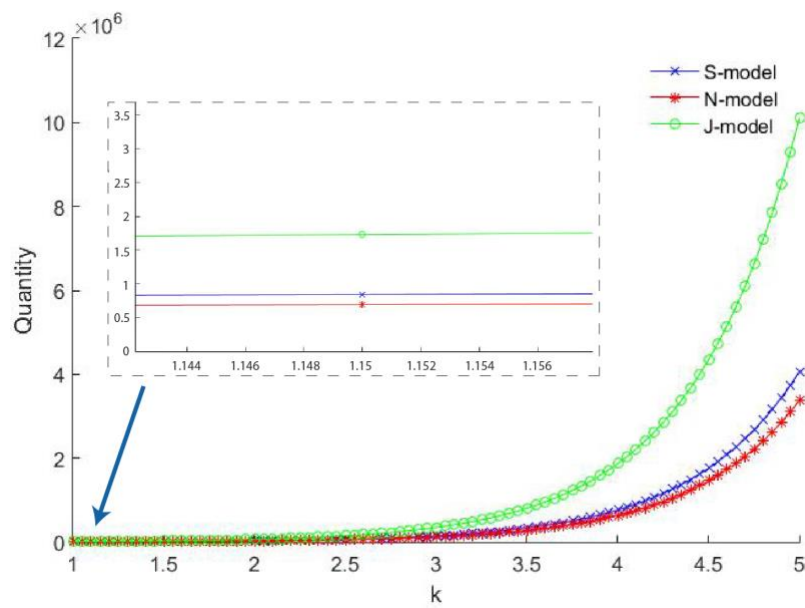
**Figure 4.** Revenue changes according to the price elasticity coefficient  $k$

- **Insight 4** Quantity of recycled product changes with the price elasticity coefficient  $k$

Figure 5 shows that the quantity of recycled product in all three models increases with a rising  $k$ , and the relationship of the quantity in these three models is:  $J\text{-model} > S\text{-model} > N\text{-model}$ . Similar to the impact of the fluctuation ratio variation on the quantity of recycled product, it can be observed that raising the price elasticity coefficient  $k$  encourages more customers to sell used products to the retailer, and if

all members of the SC make decisions in cooperation as shown in the curve of the *J-model* this results in a higher volume of recycled products.

Given the fixed retail price  $p_0$ , it can be observed that raising the price elasticity coefficient  $k$  encourages more customers to sell used products to the retailer. If all the members of the SC make their decisions cooperatively this results in a higher quantity of recycled products.

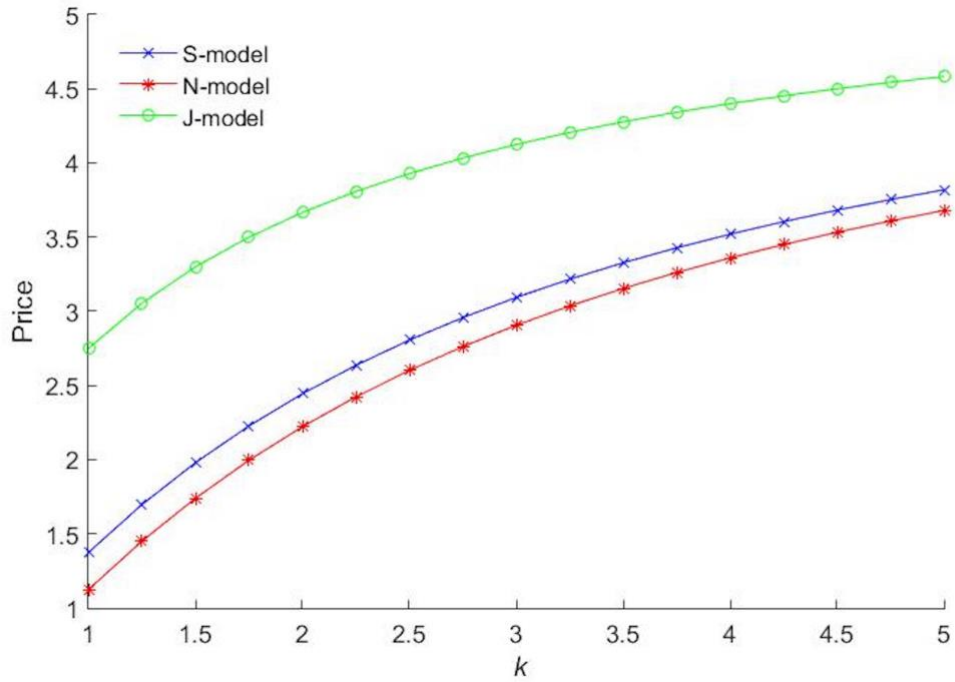


**Figure 5.** Quantity of recycled changes according to  $k$

- **Insight 5** Recycling price changes according to the price elasticity coefficient  $k$

Figure 6 shows that the recycling price increases with a rising  $k$ , and the relationship of the price in these three models is: *J-model* > *S-model* > *N-model*. It can be observed that raising the price elasticity coefficient  $k$  encourages the retailer to set a higher recycling price for customers, and helps to set a higher price if all members of the SC make decisions in cooperation.





**Figure 6.** Recycling price changes according  $k$

### 5.2.3 The combined effect of $t$ and $k$ and the unit marginal production cost of remanufactured products ( $C_m$ )

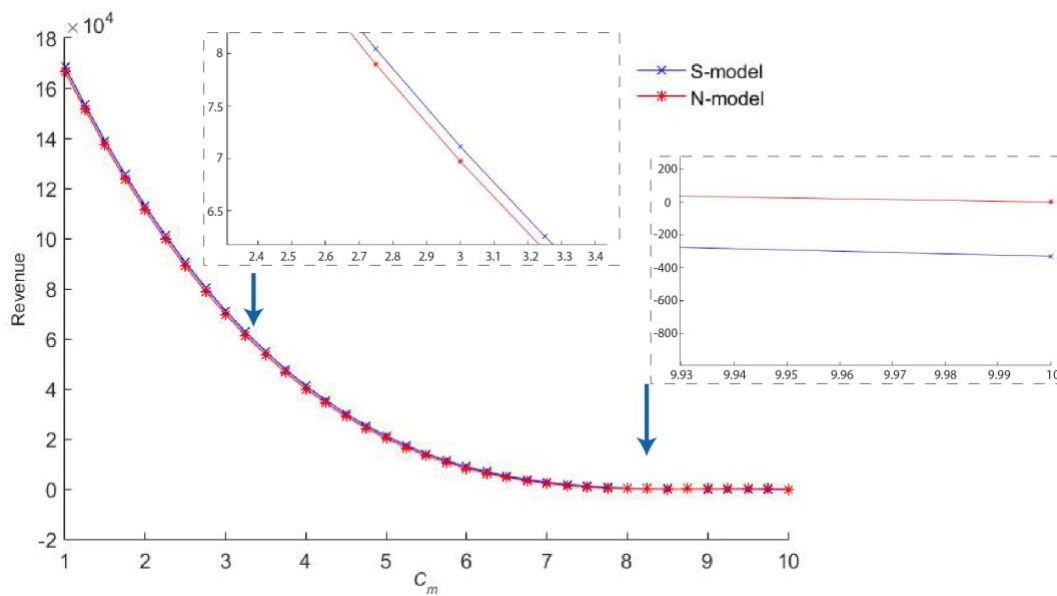
In this discussion of the combined effect of  $t$  and  $k$ , the other parameters are the same as in section 5.1 with the exception of the values of  $t$  and  $k$ , where  $t \in (0,1)$  and  $k \in (1,5)$ .

- **Insight 6** Revenue changes according to  $t$  and  $k$
- **Insight 7** Quantity of recycled changes according to  $t$  and  $k$ .

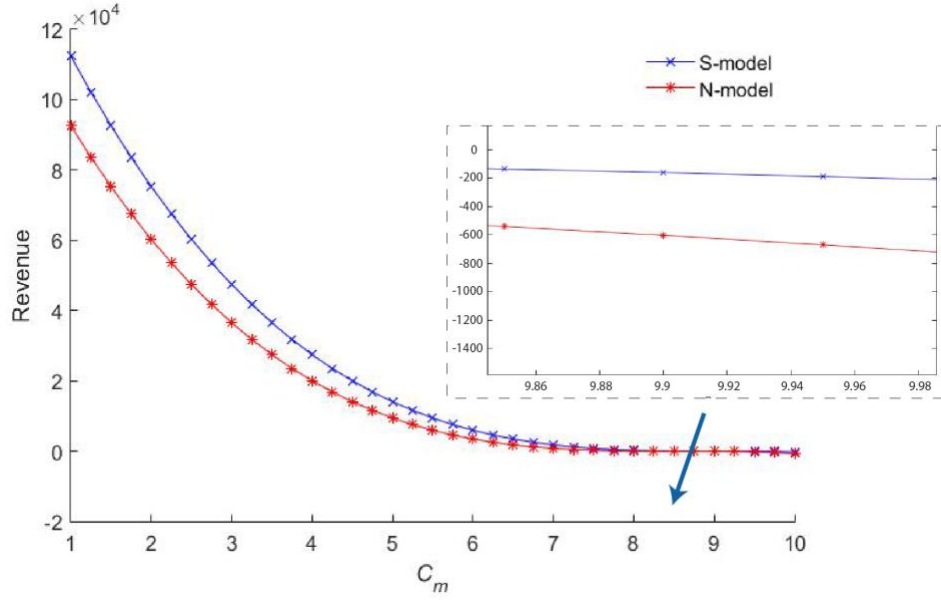
With regards to the unit marginal production cost of remanufactured products ( $C_m$ ), the parameters are the same as those in section 5.1 with the exception of the unit marginal production cost of remanufactured products  $C_m \in (1,10)$ .

- **Insight 8** Revenue changes according to the unit marginal production cost of remanufactured  $C_m$

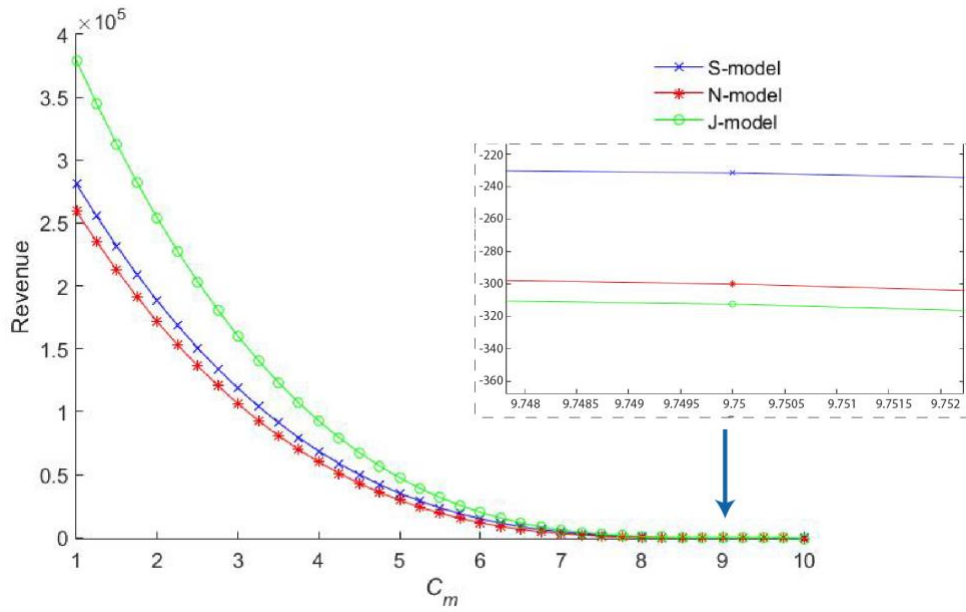
Graphs 1) and 2) in Figure 7 show that the manufacturer's and the retailer's revenues decrease with an increasing  $C_m$ . Initially, the manufacturer's revenue in the *S-model* is larger than in the *N-model*, while with an increasing  $C_m$ , the manufacturer's revenue in the *S-model* reduces faster, and less than in *N-model*. The revenue of the retailer in the *S-model* is always higher than in the *N-model*. In Graph 3) the relationship of the total reverse logistics system revenues in these three models initially is *J-model* > *S-model* > *N-model* but with an increasing  $C_m$ , the system revenue in the *J-model* reduces more quickly but less than in the *N-model* or the *S-model*; the revenue in the *S-model* is always higher than in the *N-model*.



1) manufacturer



2) retailer



3) total reverse logistics system

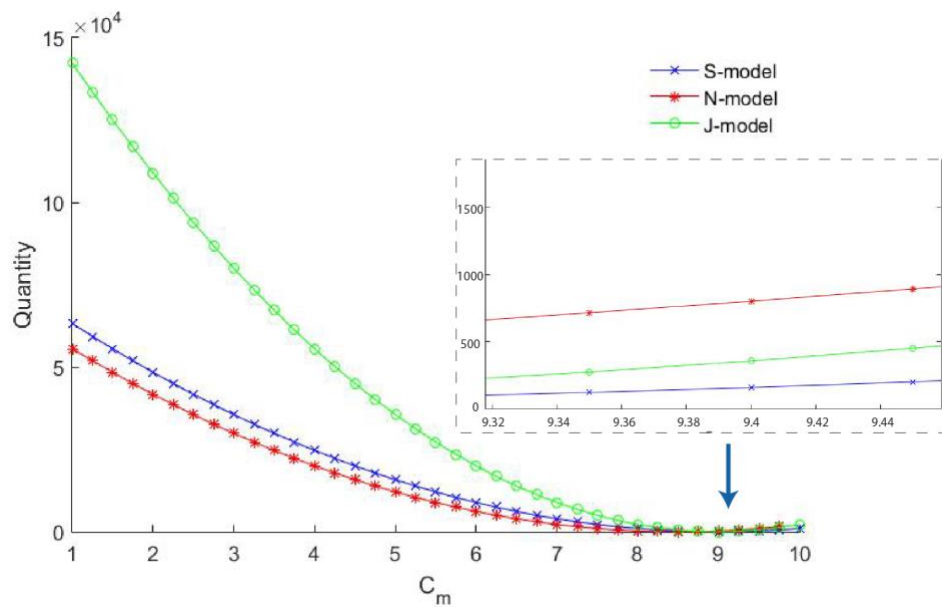
**Figure 7.** Revenue changes according to  $C_m$

It can be seen raising the unit marginal production cost of the remanufactured product  $C_m$  results in a revenue decrease for the members of the SC and the system, and that improving the production technology and reducing the unit marginal

production cost of the remanufactured product maintains the revenue at an acceptable level. If the price of the unit marginal production cost of remanufactured product is kept at a low level, it is better for the stakeholders to make their pricing and manufacturing decision cooperatively which would result also in a higher system revenue.

- **Insight 9** Quantity of recycled changes with the unit marginal production cost of remanufactured

Figure 8 shows the quantity of recycled product decreases with a rising  $C_m$ , and the relationship of the quantity in these three models initially is  $J\text{-model} > S\text{-model} > N\text{-model}$  but is increasing with  $C_m$ , the system revenue in the  $J\text{-model}$  and  $S\text{-model}$  falls more quickly but less than in the  $N\text{-model}$ , and revenue in the  $J\text{-model}$  is always higher than in the  $S\text{-model}$ .



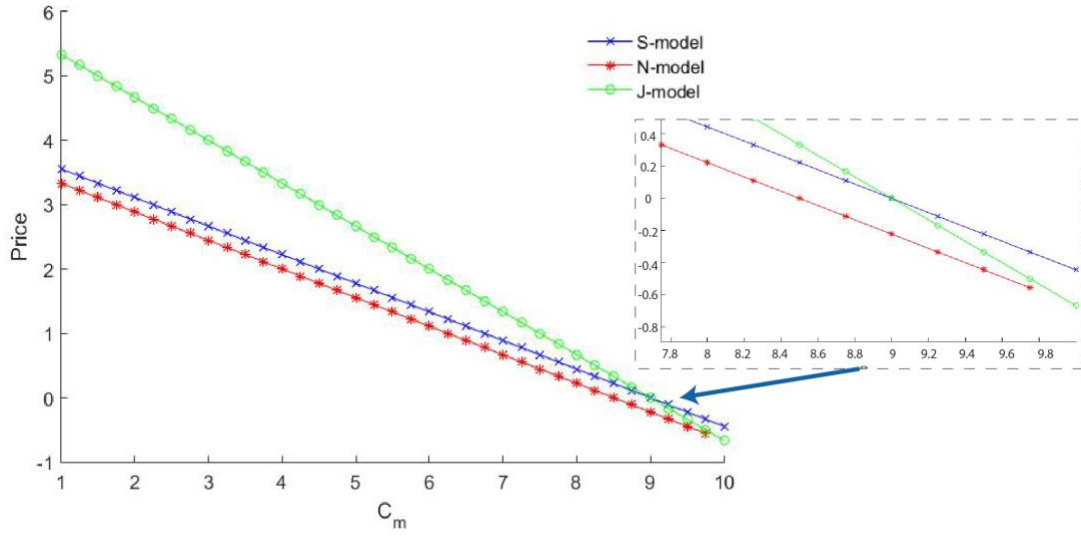
**Figure 8.** Quantity of recycled changes according to  $C_m$

It can be seen that raising the unit marginal production cost of remanufactured  $C_m$  reduces the amount of remanufactured product, results in a lower volume of the recycled product, and a lower recycling price for the retailer. If all the members of the SC make their decisions cooperatively this results in a bigger amount of recycled product if the unit marginal production cost of the remanufactured product is kept reasonably low.

- **Insight 10** Recycling price changes according to the unit marginal production cost of remanufactured

Figure 9 shows the recycling price changes for the retailer in the non-cooperative pricing scenario and joint pricing scenario (*S-model*, *N-model* and *J-model*). The recycling price decreases with a rising  $C_m$ , and the relationship of the price in these three models initially is  $J\text{-model} > S\text{-model} > N\text{-model}$  at first, but with an increasing  $C_m$ , the system revenue in the *J-model* reduces more quickly but less than in the *N-model* and *S-model* although the revenue in the *S-model* is always higher than in the *N-model*.

It can be seen that raising  $C_m$  constrains the retailer from setting a higher recycling price for customers but helps to set a reasonable price if the members of the SC make their decisions cooperatively.



**Figure 9.** Recycling price changes according to  $C_m$

As emerged from the literature review, there is a growing attention to reverse logistics issues. This is due to the rising awareness of the importance of managerial practices for supply chain sustainability and to institutional and regulatory pressures.

Overall, our models highlight the relevance of aligned goals and cooperation along the SC. First, our study points to the collective utility of the reverse logistics system as we highlight the positive effects of CEA and recycled products for the supply chain as a whole. Second, we point to the advantage for stakeholders, to cooperate for setting pricing and manufacturing decisions. We show that independent decisions lead to lower stakeholder and system revenues.

Managers can learn from the proposed models that promoting environmental awareness among customers and pursuing cooperatively decision making along the SC lead to higher system revenue. Cooperation should be fostered at all stages of the

SC to make the product greener which in turn lead to a more sustainable SC. Specifically, the volume of recycled products increases as all members of the SC cooperate by selling used products. Managers can also achieve a better understanding of the implications of producing a more price sensitive product for a better revenue.

## **6. Conclusions**

This paper focused on a reverse logistics pricing strategy in a GSC with environmentally-conscious customers in markets that lead to increased amounts of used product, and encourage GSC firms to manufacture greener and more sustainable products. The revenue functions of GSC members were formulated considering the increased supply of used product due to the increase in CEA, and solving them for the optimal solutions for GSCs' members in *J-model*, *S-model* and *N-model* of the non-cooperative pricing scenario and joint pricing scenario. We applied numerical sensitivity analyses to the effects of the fluctuation ratio of the CEA changes, the price elasticity coefficient of the recycled product changes, and the unit marginal production cost of remanufactured products, on the revenues of GSC stakeholders and their decisions about environmental pollution and sustainability.

We observed that increasing the effects of the fluctuation ratio of the CEA and the price elasticity coefficient of the recycled products to a certain threshold, leads to increases in the supply and the prices of the used product, and increases in the revenues of all GSC members. We observe also that an increase in the unit marginal production cost of remanufactured product leads to a decrease in the quantity of recycled product, the price of the recycled product, and the revenues of all GSC members. From a holistic perspective, it is better for stakeholders to make their pricing and manufacturing decisions jointly which would lead to a higher level of

revenue and quantity of recycled product.

Although this study contributes to the GSC management literature, its models are restricted to a typical reverse logistics operational scenario without new-manufactured products, in which the profit derived from selling the product is excluded from the retailer's revenue. It would be interesting to generalize the models to more than two types of products (new-manufactured and re-manufactured), and to extend the scenarios to include a closed-loop reverse SC. In the present study, the product's retail price is assumed to be fixed, and the impact of the CEA fluctuation ratio on market demand is not considered. This study could be improved by including the impacts of the retail price and the CEA fluctuation ratio on market demand. A final suggestion for further research would be to consider incorporating governmental subsidies and intervention in cording the green supply chain..

## Acknowledgment

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## Appendix A

**Proof of 1)**  $\Pi_m$  is a concave function of  $p_m$ .

Note that the variables  $p_m$  and  $\beta$  are non-negative and independent of each other.

According to Eq.(4), the first-order and the second-order derivatives of  $\Pi_m$  with



respect to  $p_m$  are as follows.

$$\begin{cases} \frac{d\Pi_m}{dp_m} = \frac{d}{1-t}(1-\beta)^k p_m^{k-1} (kp_0 - kC_m - kp_m - p_m) \\ \frac{d^2\Pi_m}{dp_m^2} = \frac{dk}{1-t}(1-\beta)^k p_m^{k-2} (C_m - p_0 - p_m + kp_0 - kC_m - kp_m) \end{cases} \quad (\text{A.1})$$

Using Eq. (A.1), we find that  $\Pi_m$  is concave in  $p_m$  when  $p_m > \frac{k-1}{k+1}(p_0 - C_m)$ .

For the GSC system, it is obvious that  $\Pi_m \geq 0$  which guarantees that the manufacturer can make a profit. So,  $p_0 - C_m \geq p_m$ . Then the value range of  $p_m$  can be addressed as:

$$\frac{k-1}{k+1}(p_0 - C_m) < p_m \leq p_0 - C_m \quad (\text{A.2})$$

**Proof of 2)  $\Pi_r$  is a concave function of  $\beta$ .**

According to Eq.(5), the first-order and the second-order derivatives of  $\Pi_r$  with respect to  $\beta$  are as follows.

$$\begin{cases} \frac{d\Pi_r}{d\beta} = \frac{d}{1-t}(1-\beta)^{k-1} p_m^k [p_m(1-\beta) - k(\beta p_m - C_r)] \\ \frac{d^2\Pi_r}{d\beta^2} = \frac{dk}{1-t}(1-\beta)^{k-2} p_m^k (C_r - 2p_m + \beta p_m - kC_r + k\beta p_m) \end{cases} \quad (\text{A.3})$$

Using Eq. (A.2), we find that  $\Pi_m$  is concave in  $\beta$  when  $\beta < \frac{2p_m + C_r(k-1)}{p_m(k+1)}$ .

For the GSC system, it is obvious that  $\Pi \geq 0$  which guarantees that the retailer can make a profit. So,  $\beta p_m - C_r \geq 0$ . Then the value range of  $\beta$  can be written as:

$$\frac{C_r}{p_m} \leq \beta < \frac{2p_m + C_r(k-1)}{p_m(k+1)} \quad (\text{A.4})$$

**Proof of 3)  $\Pi$  is a concave function of  $(p_m, \beta)$ .**

Note that the variables  $p_m$  and  $\beta$  are non-negative and independent of each other.

According to Eq.(6), the first-order partial derivatives of  $\Pi$  with respect to  $p_m$  and  $\beta$  are as follows.

$$\begin{cases} \frac{\partial \Pi}{\partial p_m} = \frac{d}{1-t} (1-\beta)^k p_m^{k-1} [k(p_0 - C_m - C_r) - (1+k)(1-\beta)p_m] \\ \frac{\partial \Pi}{\partial \beta} = -\frac{d}{1-t} p_m^k (1-\beta)^{k-1} [k(p_0 - C_m - C_r) - (1+k)(1-\beta)p_m] \end{cases} \quad (\text{A.5})$$

and the second-order partial derivatives of  $\Pi$  with respect to  $p_m$  and  $\beta$  can be written as.

$$\begin{aligned} \frac{\partial^2 \Pi}{\partial p_m^2} &= \frac{dk}{1-t} (1-\beta)^k p_m^{k-2} [(k-1)(p_0 - C_m - C_r) - (1+k)(1-\beta)p_m] \\ \frac{\partial^2 \Pi}{\partial p_m \partial \beta} &= \frac{\partial^2 \Pi}{\partial \beta \partial p_m} = \frac{d}{1-t} (1-\beta)^{k-1} p_m^{k-1} [(1-\beta)(1+k)^2 p_m - k^2(p_0 - C_m - C_r)] \\ \frac{\partial^2 \Pi}{\partial \beta^2} &= \frac{dk}{1-t} (1-\beta)^{k-2} p_m^k [(k-1)(p_0 - C_m - C_r) - (1+k)(1-\beta)p_m] \end{aligned} \quad (\text{A.6})$$

Note  $A = \frac{\partial^2 \Pi}{\partial p_m^2}$ ,  $B = \frac{\partial^2 \Pi}{\partial p_m \partial \beta}$  and  $C = \frac{\partial^2 \Pi}{\partial \beta^2}$  respectively. Then, we have the

Hessian matrix as follows.

$$H = \begin{bmatrix} A & B \\ B & C \end{bmatrix}$$

When  $A < 0$  and  $AC - B^2 > 0$  are satisfied,  $H$  is negative definite. So,  $\Pi$  is a concave function of  $(p_m, \beta)$ .

For  $A < 0$ , we obtain  $(1-\beta)p_m > \frac{k-1}{k+1}(p_0 - C_m - C_r)$ .

For  $AC - B^2 > 0$ , we obtain  $\left[ (1-\beta)p_m - \frac{2k^2(p_0 - C_m - C_r)}{(2k+1)(k+1)} \right]^2 > \left[ \frac{k(p_0 - C_m - C_r)}{(2k+1)(k+1)} \right]^2$ ,

i.e.  $(1-\beta)p_m < \frac{2k-1}{2k+1} \frac{k}{k+1} (p_0 - C_m - C_r)$  or  $(1-\beta)p_m > \frac{k}{k+1} (p_0 - C_m - C_r)$ .

For the GSC system, it is obvious that  $\Pi \geq 0$  which guarantees that the GSC system can make a profit. So,  $(1-\beta)p_m \leq p_0 - C_m - C_r$ . Given that  $k > 1$  and

$(1-\beta)p_m \geq 0$  , it is reasonable that  $\frac{k}{k+1}(p_0 - C_m - C_r) < (1-\beta)p_m \leq p_0 - C_m - C_r$  or

$0 \leq (1-\beta)p_m < \frac{k-1}{2k+1} \frac{k}{k+1}(p_0 - C_m - C_r)$  is the value range of  $(1-\beta)p_m$  as depicted in

Figure A.1, and  $A < 0$  and  $AC - B^2 > 0$  can both be satisfied, i.e.  $\Pi$  is a concave function of  $(p_m, \beta)$ .

In the proofs of 1) and 2), we obtain that  $\frac{k-1}{k+1}(p_0 - C_m) < p_m \leq p_0 - C_m$ , and

$\frac{C_r}{p_m} \leq \beta < \frac{2p_m + C_r(k-1)}{p_m(k+1)}$ , we can get  $\frac{k-1}{k+1}(p_0 - C_m - C_r) - \frac{2p_m}{k+1} < (1-\beta)p_m \leq p_0 - C_m - C_r$ .

Because  $\frac{k-1}{2k+1} \frac{k}{k+1}(p_0 - C_m - C_r) < \frac{k-1}{k+1}(p_0 - C_m - C_r) - \frac{2p_m}{k+1} < \frac{k}{k+1}(p_0 - C_m - C_r)$ , the feasible value range of  $(1-\beta)p_m$  can be expressed as Eq.(6) and is depicted in

Figure A.1.

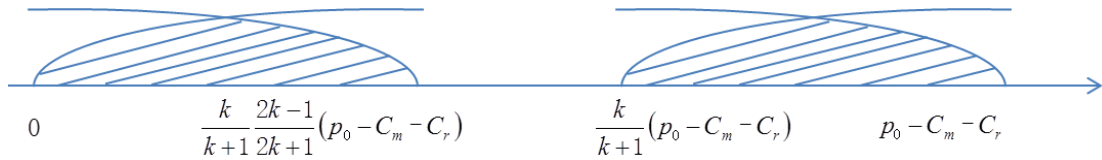
$$\frac{k}{k+1}(p_0 - C_m - C_r) < (1-\beta)p_m \leq p_0 - C_m - C_r \quad (\text{A.3})$$

In summary, when  $\frac{k-1}{k+1}(p_0 - C_m) \leq p_m \leq p_0 - C_m$ ,  $\frac{C_r}{p_m} \leq \beta \leq \frac{2p_m + C_r(k-1)}{p_m(k+1)}$ , 1)  $\Pi_m$

is a concave function of  $p_m$ ; 2)  $\Pi_r$  is a concave function of  $\beta$ ; and 3)  $\Pi$  is a

concave function of  $(p_m, \beta)$ , as  $\frac{k}{k+1}(p_0 - C_m - C_r) < (1-\beta)p_m \leq p_0 - C_m - C_r$  is also

satisfied.



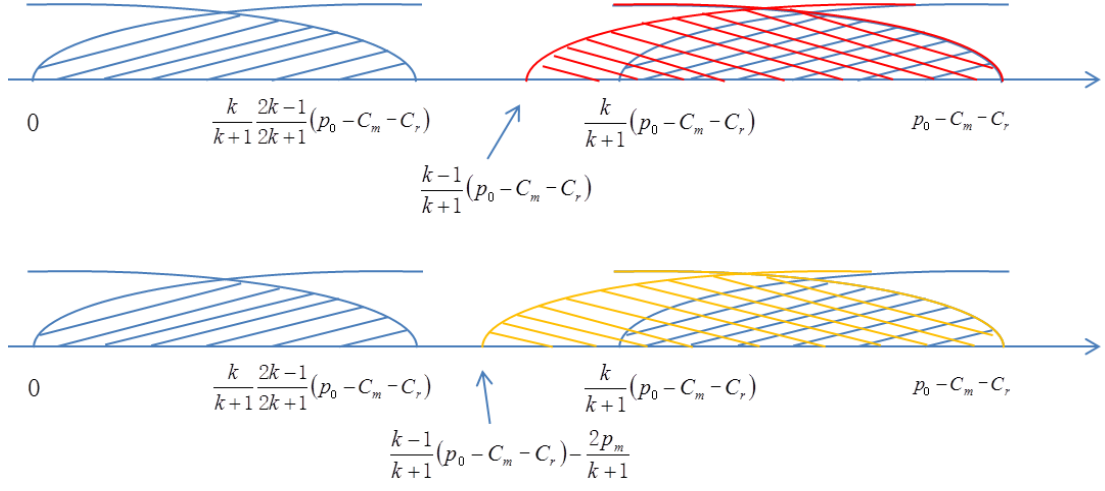


Figure A.1 the analysis of the value range of  $(1-\beta)p_m$

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