Resources, Conservation & Recycling 145 (2019) 78–85

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Inventory control and supply chain management: A green growth perspective

Qiang Wang[a], Jie Wu[a,*], Nenggui Zhao[a], Qingyuan Zhu[b,c]

[a] School of Management, University of Science and Technology of China, Hefei 230026, China
[b] College of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing 210000, China
[c] Research Centre for Soft Energy Science, Nanjing University of Aeronautics and Astronautics, 29 Jiangjun Avenue, Nanjing 211106, China

ARTICLE INFO

Keywords:
Green growth
Recycling
Government subsidy
Inventory
Green supply chain

ABSTRACT

Green growth is becoming an important mode for the sustainable operation of economy and society in the world. All countries are developing innovative methodologies to achieve green growth. Particularly, inventory and pricing are important technologies for companies' leadership to make decisions. The increasingly polluted environment has made sustainable utilization of resources and environmental protection more urgent, however, there is very little literature studying inventory and pricing from a green growth perspective. To fill this gap, we consider both inventory and pricing decisions for companies under different green growth mechanisms. We first consider the single period inventory model with a remanufactured supplier and the government subsidy for single and dual sourcing system, respectively, further derive the optimal order decisions for the retailer. Then, we assume the customers are environmentally sensitive and there is a green supplier in the market, examine the optimal pricing decisions for the retailer using the two-stage optimization method. We explore the value of the recycling supplier and government subsidy in the numerical study; furthermore, we examine the influences of the green degree of product on the optimal price decisions for different products. One interesting finding is that the retailer should order more green products no matter how expensive it is, as long as the customers in the market are environmentally sensitive.

1. Introduction

Innovative technology for green growth is becoming urgent due to environmental problems caused by industrialization have increasingly attracted the attention of the government and the public, and the government has paid more and more attention to enhancing the environmental awareness of enterprises (Yang et al., 2017; Song et al., 2018). As the environmental management system (EMS) matures, environmental considerations can be integrated into all business decisions. Due to the increasingly stringent environmental requirements of the government and the public, producers of supply chains have to start focusing on environmental performance. Production of green products usually involves recycling. Waste products are recycled and remanufactured, turn into new products, which can realize the reuse of resources and reduce environmental pollution. Consumers are increasingly aware of the environmental impact of products, thereby some regulations related to resource recycling and production of green products has arisen (Yang et al., 2018; Winslow et al., 2018).

Green products with an environmental label, which is a notarized appraisal of the environmental performance and a comprehensive evaluation of the environmental quality of products. The environmental label is the green identity card of products for enterprises, and it is very helpful for enterprises to get government support and consumer trust as well as carry out green marketing smoothly. If the enterprise obtains the green sign, it means that production, use, and treatment process of the product meet the requirements of environmental protection, no harm to human health, and its salvage is harmless, in favor of the resource regeneration and recycling. Producers often put a small investment in green innovation research and development because of insufficient funds, and the price of green products is often higher, producers are difficult to obtain a favorable competitive position in the market, resulting in an insufficient motivation to produce green products. The development of green products is inseparable from government support. In order to deal with the predicament of the development of green products, the government usually uses the subsidy to stimulate the production of green products and has achieved significant results.

* Corresponding author.
E-mail addresses: qiangwan@mail.ustc.edu.cn (Q. Wang), jacky012@mail.ustc.edu.cn (J. Wu), zhaoneng@mail.ustc.edu.cn (N. Zhao), zqynuaa@nuaa.edu.cn (Q. Zhu).

https://doi.org/10.1016/j.resconrec.2019.02.024
Received 23 November 2018; Received in revised form 19 February 2019; Accepted 19 February 2019
0921-3449/

Remanufacturing is a reflection of green growth technology. Although the negative impact of remanufactured products on the environment is significantly lower, consumers have low chance of accepting these products. Thus, the governments, especially in developing countries usually provide subsidies to remanufacturers to facilitate the remanufactured products use more. For instance, in China, if the remanufacturers recycled and remanufactured the used products, the Chinese government will provide a subsidy for such remanufactures to encourage the remanufacturers' environmental action (Zhao et al., 2018). Even some remanufacturers give some part of their subsidies to customers to appeal to customers to use remanufactured products. Thus the government subsidy may not cause the cost reduction of the remanufacturers, whereas it can stimulate the protection of the environment. Based on this, how to decide the amount of the government subsidy for the remanufacturers is still a difficult problem.

Pricing and inventory policies as innovative technologies are very important for companies when they are making decisions. In this paper, we are based on inventory and supply chain system, consider the optimal order and pricing policies at the different environmental protection perspectives. First, we consider a single sourcing system, which has only one retailer and one supplier, compute how many products the retailer should order from the supplier through a classical newsvendor approach. Next, we consider the case that the products can be recycled, which is equivalent to the two suppliers (one of them is the remanufacturer) in the marker. In such situation, how do retailer make order decisions from two supply options? Then, we study the case where the retailer's order policy when there are two different suppliers in the original market, one of the suppliers is recycling supplier, who can receive the government subsidy if he/she provides retailer products. Finally, we consider another green growth mechanism, where one of the suppliers provide green products to the retailer, while another supplier provide a common product, the retailer provides two different products to customers. Customers are sensitive to different products. In such cases, we study how retailer make pricing strategy for different products.

To achieve research goals, we organize the remainder of the paper as follows. In Section 2 we review related literature. The classical newsvendor problem with or without a remanufactured supplier, and government provide the subsidy for the remanufactured supplier are presented in Section 3. In Section 4 we study the pricing strategy of the retailer when considering another green growth mechanism-green product. Section 5 concludes.

2. Literature review

There are mainly two research streams related to our works, i.e., inventory problem with environmental concerns and supply chain management with environmental concerns. It is very significant for companies to decide how much inventory to hold and how much to order from a supplier. Pricing decision often occurs in supply chain management, and pricing decisions of the companies are also critical.

There are several researches studying inventory problem with environmental impact. Van Der Laan (1997) presented an experimental analysis to examine the effects of remanufacturing on inventory control. Van Der Laan et al. (1999) studied an inventory control problem in a special system where the manufacturer has remanufacturing capabilities. Mahadevan et al. (2003) considered a remanufacturing equipment that receives recycling products which are as same as new products follows a Poisson process, derived some counter-intuitive conclusions and checked the performance of the heuristic policy on a set of examples. Roy et al. (2009) considered an inventory system with remanufacturing for a single product in a finite horizon, and assumed that the remanufactured products are regarded as completely new. El Saadany and Jaber (2010) presented deterministic mathematical models for multiple remanufacturing and production cycles. Hua et al. (2011) studied the firms manage carbon footprints in an inventory system and got the optimal policy. Bouchery et al. (2012) studied the constraints of carbon emission based on a traditional economic order quantity (EOQ) model. Similar researches are inducted by Chen et al. (2013) and Absi et al. (2013). Jaber et al. (2013) constructed a manufacturer-retailer supply chain model and used a classic inventory approach to examine the performance of various emission trading mechanisms such as carbon tax and emissions penalty. A stochastic inventory problem is studied by Song and Leng (2012), they considered the one-period production problem under different carbon emission policies and obtained the optimum production quantity. In our paper, we focus on single-period, single sourcing and dual sourcing inventory model with green growth mechanism. Rosič and Jammernegg (2013) considered the environmental impact of transport and carbon emission limit by constructing a dual sourcing newsvendor model. Arıkan and Jammernegg (2014) studied the carbon footprint constraint problem of products based on a classic one-period inventory model.

The second research stream is supply chain management with environmental concerns. Considering sustainability development problem in the supply chain management field is increasingly important (Castillo et al., 2018). Some literature from different perspectives, such as operational, enterprise decision and environmental protection to study supply chain management problems (Guide et al., 2000; Guide et al., 2003; Savaskan et al., 2004; Mallidis et al., 2012; Fahimnia et al., 2015; (Ding et al., 2016); Zhu and He, 2017). Recently, various researchers have studied how to use innovative technology to promote economic green growth and resources' sustainable management in production and operations management society. As an example, Nagurney et al. (2007) considered a problem whose objectives are maximizing the revenue and minimizing the emissions by constructing a supply chain model. Govindan et al. (2014) focused on judging obstacles from the perspective of procuring efficiency in a green supply chain. Ma et al. (2013) explored the role of consumption subsidy provided by the government on improving supply chain performances and showed that all the consumers that choose to buy the remanufactured products are winners of the subsidy provided by the government in different degrees. Sheu and Chen (2012) constructed a game theory model (which is three stage) to analyze the influences of government economic intervention on supply chain green management. Gunasekaran et al. (2015) reviewed the existing research on the green supply chain management, environmental protection awareness and sustainability operation, thereby proposed an abstract conceptual model to indicate the relevance between the above three variables using manufacturing firms of Malaysian as an example. Li et al. (2016) considered a green dual channel supply chain and showed that the greening costs of products have significant influences on the decisions of green degree and the retail price. Carvalho et al. (2017) proposed a mathematical model to provide managerial insights for the decision maker to improve the efficiency of the supply chain, and showed that not all firms can be completely lean or green in the supply chain context. Xu and Wang (2018) studied the decisions in a closed-loop supply chain with pollution reduction and retailer recycling behavior. Ghadimi et al. (2019) analyzed the published research works in Resources, Conservation and Recycling journal in the setting of the sustainable supply chain, expounded the present situations, future challenges, development directions and chances for sustainable operations. Recently, several other studies involve the green supply chain management (Coskun et al., 2016; Carvalho et al., 2017; Tseng et al., 2018; Tseng et al., 2019).

The contributions of this paper are threefold. First, provide the optimal order policies for the retailer based on single sourcing newsvendor approach with or without recycling supplier. Second, we extend the single sourcing setting to dual sourcing newsvendor system when the government subsidy are considered. Finally, investigate the pricing decisions for the retailer when the customers are sensitive to the environmental protection products, i.e., green product, and the green degree will conversely affect demand comes from sensitive customers.

3. Inventory control with environmental concerns

In this section, we study the inventory policies under different inventory systems: single sourcing inventory system with and without remanufactured supplier who can lead to green growth, and dual sourcing inventory system with government subsidy.

3.1. Single sourcing system without remanufacturing

We first consider the classical single sourcing newsvendor problem, which is a classical one-period inventory control problem. Before the selling season, demand, denote as D is a nonnegative random variable, which distributed as a cumulative distribution function $F(.)$ and density function $f(.)$. Denote the order quantities of the retailer as q units, which comes from the supplier with the ordering cost is c per unit and the sale price is p per unit. In a selling horizon, if the order quantities of the retailer is larger than the realized demand, some excess inventory (leftovers) will be left and which can be sold to the customers at the price (salvage cost) s per unit; If q is less than the demand, overmuch demand will be lost (lost sales). To make the model meaningful, we supposed that $s < c < p$. Denote the leftovers as $L_1(q)$ and lost sales as $L_2(q)$, then we have

$$\mathbb{E}(L_1(q)) = \int_0^q (q-x)f(x)\,\mathrm{d}x$$

and

$$\mathbb{E}(L_2(q)) = \int_q^\infty (x-q)f(x)\,\mathrm{d}x$$

Then, the expected profit denoted as $\Pi(q)$ of the retailer is

$$\Pi(q) = (p-c)q - (p-s).\ \mathbb{E}(L_1(q)).$$

Obviously, $\Pi(q)$ is concave with respect to q. Thus the optimal q^* is given by newsvendor fractile as follows

$$q^* = F^{-1}\left(\frac{p-c}{p-s}\right). \tag{1}$$

This is the optimal order policy in a single sourcing inventory model. In such a model, we assumed that the retailer makes order decision from the supplier before the selling horizon, and no other ordering once the initial order decision is made.

3.2. Single sourcing system with remanufacturing

In practice, many old or waste products can be reprocessed and then be reused. In this section, we consider an inventory system with only one initial supplier, where the waste products can be recycled and remanufactured, thus the classical single sourcing system becomes a two sources system. It is convenient to imagine that there are two managers (suppliers), one supplier only provides products that completely new to the retailer while the other can recycle the waste products and sell it to the retailer after reprocessing, which becomes a dual sourcing inventory model. Since the waste products need to be reprocessed and then sell it to the customers, thus the orders from the recycling channel will be cheap but slow while the orders from the initial channel are expensive but fast. Here, the recycling channel is called the regular supplier and the initial channel is called the emergency supplier. The regular (recycling) supplier only sell products before the selling horizon and the demand is random. We assume that the emergency (initial) supplier not has capacity constraints and could respond rapidly when demand changes. In fact, we can regard the emergency supplier as backup one to satisfy the excess demand which can not be fulfilled by the regular supplier. Of particular note is the order decision of the regular supplier should be finished before demand is known whereas the orders from the emergency supplier are decided until the actual demand is realized. Such an order sequence is quite common, for example, purchase new electronic products with old products by offering a price difference.

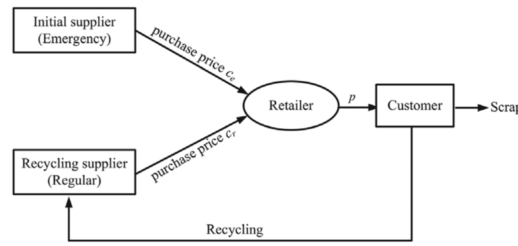


Fig. 1. Recycling system.

Recycling system framework that we considered as shown in Fig. 1. In such a recycling system, the products are sold at the same sale price of p per unit, but the acquisition prices of two suppliers are different. Denote the acquisition price (order cost) from the recycling channel as c_r while the acquisition price from the initial channel as c_e. Since the products from the recycling channel are reprocessed, so the acquisition price from such channel is usually low, that is $c_r \le c_e$. Let $\tilde{c} \doteq c_e - c_r$ be the premium cost per unit. Assume that excess inventory which ascribes to the recycling retailer could be sold at a salvage value s per unit at the end of the sales horizon. Similarly, we assume $p > c_r > s$. All the notation are summarized in Table 1.

Let $\pi(q^r, x)$ be the retailer's profit, which depends on the order quantity q^r from the recycling channel and the realized demand x, then we have

$$\pi(q^r, x) = \begin{cases} \mathrm{px} - c_r q^r + s(q^r - x) & \text{if } x \le q^r \\ \mathrm{px} - c_r q^r - c_e(x - q^r) & \text{if } x > q^r \end{cases} \tag{2}$$

When $x \le q^r$, the demand is fulfilled only by the recycling supplier and any excess inventory is able to be processed with the salvage value s per unit. For $x > q^r$, the recycling supplier can not satisfy the outside demand, thus some other orders from the initial emergency supplier are placed to satisfy the excess demand. Denote $\pi(q^r)$ as the retailer's expected profit, which is given as follows

$$\begin{aligned} \Pi(q^r) &= \mathbb{E}[\pi(q^r, x)] \\ &= \int_0^{q^r} (\mathrm{px} - c_r q^r + s(q^r - x))f(x)\mathrm{dx} + \int_{q^r}^\infty (\mathrm{px} - c_r q^r \\ &\quad - c_e(x - q^r))f(x)\mathrm{dx} \\ &= p\mathbb{E}(X) + s\mathbb{E}(q^r - X)^+ - c_r q^r - c_e\mathbb{E}(X - q^r)^+ \end{aligned} \tag{3}$$

Which relies on the order quantity from the recycling channel q^r and a random demand variable X. Here, $(x)^+ = \max(x, 0)$ and $\mathbb{E}(.)$ means the expected value. Eq. (3) means that the expected profits composes of the incomes with p selling price per unit during the selling horizon and the total salvage value with s per unit at the end of the selling horizon, minus the ordering cost from the recycling supplier and the ordering cost from the initial emergency supplier with c_e per unit.

The above problem is a newsvendor problem with a remanufactured supply option. We can imagine such case: when there is out of stock, some customers may choose to wait until their demand is satisfied with an initial (emergency) supply option. The above extended newsvendor problem is solved by Khouja (1996).

Using Leibniz's rule, we can get the first and second derivatives of the $\Pi(q^r)$ with regard to q^r as follows

$$\frac{d\Pi(q^r)}{\mathrm{d}q^r} = (s - c_r)\int_0^{q^r} f(x)\mathrm{dx} + (c_e - c_r)\int_{q^r}^\infty f(x)\mathrm{dx}, \tag{4}$$

$$\frac{d^2\Pi(q^r)}{dq^{r2}} = (s - c_e)f(q^r) < 0, \tag{5}$$

we can show that $\Pi(q^r)$ is concave. Let $F(q) = \int_0^q f(x)\mathrm{dx}$, because of continuity, $1 - F(q) = \int_q^\infty f(x)\mathrm{dx}$, denote q_*^r as the optimal order quantity from the recycling channel, then the sufficient optimality condition is

$$q_*^r = F^{-1}\left(\frac{c_e - c_r}{c_e - s}\right), \tag{6}$$

which is the well known fractile formula. Fractile $\frac{c_e - c_r}{c_e - s}$ is the probability of the case where the order quantity from the recycling channel q^r is larger than or equal to the actually realized demand. In this paper, we did not consider the fixed ordering cost and thus the ordering can be placed anytime. The optimal recycling order quantity depends on the ordering costs of the two different suppliers and salvage value of the products incurred by overstocking of products (an excess of supply over demand). Comparing with newsvendor problem with single supplier, if the ordering cost difference between two suppliers $(c_e - c_r)$ is larger than $c_e - s$, i.e., $c_e - c_r \geq c_e - s$, the demand is exclusively satisfied by the recycling supplier; if $c_e - c_r < c_e - s$, some orders will be placed by the initial emergency supplier, that is the ordering decision of the recycling supplier is made before the sales start, then the order quantity from the initial emergency supplier is placed to meet the demand requirement that is not able to be satisfied by the recycling supplier. Obviously, the expected emergency order quantity, denote as q^e, is given by

$$q^e = \mathbb{E}(X - q^r)^+. \tag{7}$$

In view of the operation process of dual sourcing system, it can mimic both single recycling supplier system and single initial supplier system, thus the ordering policies with two supply choice outperform the policies with only one supply option under expected profit perspective (see Klosterhalfen et al., 2011). More important, the dual sourcing strategy can lead to a higher service level. Furthermore, the amount of the recycling order quantity in recycling system is usually smaller than that in the inventory system with only one supplier, the reason is that some demand may be satisfied by the initial emergency supplier. One direct result can be derived from Eq. (6), the larger $c_e - c_r$ is, the more products are ordered from the recycling supplier, as a result of the cost advantage appeals the retailer orders more from the recycling channel.

In the previous section, we consider the retailer can replenish its inventory by two suppliers, especially through a recycling supplier. Such a system based on an original single source system. In reality, the market always has more than one supplier. To simplify the analysis, next we consider the case that the original system has two types of suppliers, the express and the regular, where the express supplier is quicker and more expensive, while the regular supplier is cheaper but slower. We summarize all the notations in Table 1.

3.3. Dual sourcing system with government subsidy

In this section, we consider a dual sourcing system based on the green growth perspective, which refers to the mode of economic growth in which natural resources can be used in a sustainable way. The realization of green growth is far from enough to rely on the strength of the government, it also requires the whole society to cooperate in order to achieve the desired goals. In practice, the government always provide a subsidy for the retailers if they make procurement from a "green" channel. Assume there are two different suppliers in the market, i.e., the regular and the emergency, the regular supplier provides reprocessed products while the emergency supplier provides common products. At any order period, the retailer can make orders from two different suppliers. If the retailer makes order decisions from the regular supplier, whose products are reprocessed by the waste products that received from the customer, he/she will receive the additional subsidy from the government to encourage the retailer's environmental protection consciousness. The government subsidy per product unit is denoted by a. To understand better, we can regard the order cost per unit from the regular supplier is $c_r - a$, then the government subsidy should be included in the retailer's objective function. Similar to (3), the retailer's expected profit is

$$\Pi(q^a) = p\mathbb{E}(X) + s\mathbb{E}(q^a - X)^+ + \mathrm{a}q^a - c_r q^a - c_e\mathbb{E}(X - q^a)^+, \tag{8}$$

then the optimal regular order quantity can be derived directly by simple first-order derivative condition, then we have

$$q_*^a = F^{-1}\left(\frac{c + a}{c_e - s}\right). \tag{9}$$

Here q_*^a denotes the optimal regular ordering when we considering the government subsidy. Obviously, with increasing the government subsidy a, which is equivalent to the cost advantage between two suppliers is increasing and the retailer will order more from the regular supplier. Thus, the government can control the recycling order quantity by adjusting the size of the subsidy.

4. Price decisions with green products

In the preceding section, we analyze the order policies under the single sourcing inventory system and dual sourcing inventory system with environmental protection concerns. We do not consider the customers' sensitivity on the different products ordered from the various channel, i.e., consumers are assumed to be insensitive to the green "product" and thereby decide the order quantities from two different suppliers. In reality, the consumers always prefer to green product due to their environment conservation consciousness. We can regard the remanufacturered product mentioned above as the green product. In this section, we consider there are two suppliers and an independent retailer in the market. Supplier 1 provides green product while Supplier 2 provides conventional product to the same retailer who sells two types of products to customers. We assume customers of the market are sensitive to products, i.e., some part of customers are more willing to purchase green products.

Following Choi (1996),McGuire and Staelin (1983), Kurata et al. (2007), we suppose the demand functions of the sensitive and the insensitive customers are liner in prices and green degree of the products, then the demand functions can be written as below:

$$D_1 = \theta a - b_1 p_1 + n_1 p_2 + k_1 g \tag{10}$$

$$D_2 = (1 - \theta)a - b_2 p_2 + n_2 p_1 - k_2 g, \tag{11}$$

Table 1
Notation

	Description		Description
$F(.)$	Cumulative distribution function	$f(.)$	probability density function
p	Selling price of product in inventory system	q	Order quantity without remanufacturing
c	Order cost without remanufacturing	s	Unit salvage cost of leftover inventory
$L_1(q)$	leftover inventory	$L_2(q)$	lost sales
x	Realized demand	c_e	Order cost from initial supplier
c_r	Order cost from remanufactured supplier	$(.)^+$	max(. , 0)
q^e	Order quantity from initial supplier	q^r	Order quantity from remanufactured supplier
a	Value of government subsidy	q^a	Order quantity from remanufactured supplier with government subsidy
p_1	Selling price of product 1	p_2	Selling price of product 2
g	Green degree of product 1	θ	Loyalty degree of supplier 1

where D_1 represents the demand to the product 1, i.e., green product, D_2 is the demand to the conventional product. a means the level of base demand, the share of this base demand comes from Supplier 1 is θ. Denote $a_1 = \theta a$ and $a_2 = (1-\theta)a$, a_1 and a_2 represent the base demand to the two products, obviously $a_1 = a_2$ if the base demand provided by two suppliers are same. p_1 and p_2 represent the selling price of two products. Note that g represents green degree of product, customers that have environmental protection awareness will purchase more green product as g increases. To make model simple, the cross-price effects are supposed to be symmetric, i.e., $n_1 = n_2 = n$. Obviously, $b_1 \geq n$, $b_2 \geq n$ and $k_1 \geq k_2$. Denote c_0 is the cost by ordering from the general supplier (Supplier 2), and the order cost of the retailer from Supplier 1 is expected to increase in the quoted green degree g, to simplify model, the order cost of the retailer from the Supplier 1 is denoted as $c_0 + \alpha g$. For the model to make sense, from $D_1 \geq 0$ and $D_2 \geq 0$, we have

$$c_0 + \alpha g \leq p_1 \leq A_1 g + M_1, \tag{12}$$

$$c_0 \leq p_2 \leq A_2 g + M_2, \tag{13}$$

where $A_1 = \frac{k_1 b_2 - k_2 n}{b_1 b_2 - n^2}$, $A_2 = \frac{k_1 n - k_2 b_1}{b_1 b_2 - n^2}$, $M_1 = \frac{a_1 b_2 + a_2 n}{b_1 b_2 - n^2}$, $M_2 = \frac{a_1 n + a_2 b_1}{b_1 b_2 - n^2}$. The retailer's profit is determined by

$$\begin{aligned}\Pi_r &= (p_1 - c_0 - \alpha g)D_1 + (p_2 - c_0)D_2 \\ &= (p_1 - c_0 - \alpha g)(a_1 - b_1 p_1 + \text{n}p_2 + k_1 g) + (p_2 - c_0)(a_2 - b_2 p_2 \\ &\quad + \text{n}p_1 - k_2 g)\end{aligned} \tag{14}$$

Next, we analyze the price decisions of the retailer and his optimal profit as the green products and sensitive customers are considered. To maximize the profit of the retailer, we have the first proposition as follows.

Proposition 1. *The profit of retailer Π_r is strictly jointly concave in p_1 and p_2, but not jointly concave in p_1, p_2 and g.*

Proof. According to (14), we deriving the partial derivatives of Π_r in respect of p_1 and p_2, then we get the following determinant of Hessian Matrix

$$\begin{vmatrix} \frac{\partial^2 \Pi_r}{\partial p_1^2} & \frac{\partial^2 \Pi_r}{\partial p_1 \partial p_2} \\ \frac{\partial^2 \Pi_r}{\partial p_2 \partial p_1} & \frac{\partial^2 \Pi_r}{\partial p_2^2} \end{vmatrix} = \begin{vmatrix} -2b_1 & 2n \\ 2n & -2b_2 \end{vmatrix} = 4b_1 b_2 - 4n^2 > 0,$$

and $\frac{\partial^2 \Pi_r}{\partial p_1^2} = -2b_1 < 0$, thus Π_r is strictly jointly concave in p_1 and p_2.

$$\begin{vmatrix} \frac{\partial^2 \Pi_r}{\partial p_1^2} & \frac{\partial^2 \Pi_r}{\partial p_1 \partial g} \\ \frac{\partial^2 \Pi_r}{\partial g \partial p_1} & \frac{\partial^2 \Pi_r}{\partial g^2} \end{vmatrix} = \begin{vmatrix} -2b_1 & k_1 + \alpha b_1 \\ k_1 + \alpha b_1 & -2\alpha k_1 \end{vmatrix} = 4\alpha k_1 b_1 - (k_1 + \alpha b_1)^2,$$

the above equation may be negative, thus Π_r is not jointly concave in p_1, p_2 and g. □

Proposition 1 shows that we can not obtain the optimal p_1, p_2 and g only by first-order derivative. But given g, the optimal p_1 and p_2 can be computed by simple first-order condition. Thus, we use two-stage optimization method, that is, we first compute the optimal p_1 and p_2 given g, then optimize g to maximize the retailer's profit $\Pi(g)$.

Proposition 2. *For any given g, the optimal p_1 and p_2 are given by*

$$p_1^*(g) = \frac{1}{2}(A_1 g + \alpha g + M_1 + c_0), \tag{15}$$

$$p_2^*(g) = \frac{1}{2}(A_2 g + M_2 + c_0), \tag{16}$$

which satisfies (12) and (13), and the optimal retailer's profit is

$$\begin{aligned}\Pi_r^*(g) = \frac{1}{4}\Big[&(A_1 g - \alpha g + M_1 - c_0)(k_1 g - \alpha b_1 g + \text{n}c_0 - b_1 c_0 + a_1) \\ &+ (A_2 g + M_2 - c_0)(-k_2 g + \alpha \text{n} g + \text{n}c_0 - b_2 c_0 + a_2)\Big].\end{aligned} \tag{17}$$

Proof. Computing the partial derivative of Π_r in respect of p_1 and p_2, then

$$\begin{cases} \partial \Pi_r / \partial p_1 = -2b_1 p_1 + 2np_2 + (k_1 + \alpha b_1)g + b_1 c_0 - \text{n}c_0 \\ \qquad + a_1 \\ \partial \Pi_r / \partial p_2 = -2b_2 p_2 + 2\text{n}p_1 - (k_2 + \alpha n)g - \text{n}c_0 + b_2 c_0 \\ \qquad + a_2 \end{cases}$$

$$\begin{aligned} p_1^*(g) &= \tfrac{k_1 b_2 - k_2 n + \alpha b_1 b - 2 - \alpha n^2}{2(b_1 b_2 - n^2)} g + \tfrac{b_1 b_2 - n^2}{2(b_1 b_2 - n^2)} c_0 + \tfrac{a_2 n + a_1 b_2}{2(b_1 b_2 - n^2)} \\ &= \tfrac{1}{2}(A_1 g + \alpha g + M_1 + c_0), \\ p_2^*(g) &= \tfrac{k_1 n_2 - k_2 b_1}{2(b_1 b_2 - n^2)} g + \tfrac{b_1 b_2 - n^2}{2(b_1 b_2 - n^2)} c_0 + \tfrac{a_2 b_1 + a_1 n}{2(b_1 b_2 - n^2)} \\ &= \tfrac{1}{2}(A_2 g + M_2 + c_0). \end{aligned}$$

From (12) and (13), we have

$$\begin{aligned} p_1^*(g) &= \tfrac{1}{2}(A_1 g + M_1) + \tfrac{1}{2}(\alpha g + c_0) \geq \tfrac{1}{2}(\alpha g + c_0) + \tfrac{1}{2}(\alpha g + c_0) \\ &\qquad = \alpha g + c_0, \\ p_1^*(g) &= \tfrac{1}{2}(A_1 g + M_1) + \tfrac{1}{2}(\alpha g + c_0) \leq \tfrac{1}{2}(A_1 g + M_1) + \tfrac{1}{2}(A_1 g + M_1) \\ &\qquad = A_1 g + M_1, \\ p_2^*(g) &= \tfrac{1}{2}(A_2 g + M_2) + \tfrac{c_0}{2} \geq \tfrac{c_0}{2} + \tfrac{c_0}{2} = c_0, \\ p_2^*(g) &= \tfrac{1}{2}(A_2 g + M_2) + \tfrac{c_0}{2} \leq \tfrac{1}{2}(A_2 g + M_2) + \tfrac{1}{2}(A_2 g + M_2) \\ &\qquad = A_2 g + M_2, \end{aligned}$$

thus, p_1^* and p_2^* satisfies the constraints (12) and (13). Substitute (15) and (16) into (14), (17) is obtained. □Note that clearly the green degree of product 1 g has an upper bound, denote it as $g \in [0, u]$. $g = 0$ represents the green degree as zero, in such case, product 1 becomes a conventional product, which is the same as product 2. By proposition 2, to find the optimal g to maximize $\Pi_r(g)$, we compute the partial derivative of $\Pi_r(g)$ in respect of g, then the optimal green degree g can be found from these choices, i.e., the value such that the first-order be zero, $g = 0$ and $g = u$. Denote the optimal green degree as g^*, then the optimal retail price for two products and retailer's profit are derived by (15) and (16) directly.

Furthermore, we can examine the effects of the green degree g on the optimal retail price $p_1^*(g)$ and $p_2^*(g)$. Differentiate $p_1^*(g)$ and $p_2^*(g)$ in respect of g, we find $\frac{\partial p_1^*(g)}{\partial g} \geq 0$, and $\frac{\partial p_1^*(g)}{\partial g} \geq \frac{\partial p_2^*(g)}{\partial g}$, which means $p_1^*(g)$ increases with g is increasing, the reason is that an increase in g directly lead to ordering cost from supplier 1 increase, thus its selling price will increase. $\frac{\partial p_1^*(g)}{\partial g} \geq \frac{\partial p_2^*(g)}{\partial g}$ means the effect of green degree g on $p_1^*(g)$ is larger than on $p_2^*(g)$, the reason is that g has a direct influence on demand from supplier 1 while has a cross-influence on demand from supplier 2.

5. Numerical study

A numerical experiment is implemented in this section to obtain more insights based on our previous single period inventory systems with environmental protection concerns and supply chain system with green products. We first analyze the value of adding a recycling supplier for the single sourcing system, then investigate the impact of the government subsidy on the order decision of the retailer. Finally, we explore the optimal green level of "green" supplier and the price decisions for the retailer with the system parameters θ and α change.

Table 2
Base case parameters

Selling price of product in inventory system p	15
Order cost without remanufacturing c	10
Unit salvage cost of leftover inventory s	5
Order cost from initial supplier c_e	10
Order cost from remanufactured supplier c_r	8
Demand function $F(.)$	Unif(50,250)
Selling price of product in inventory system p	15

Table 3
Results of systems with and without recycling supplier

c_r	q^*	q_r	$\Pi(q^*)$	$\Pi(q_*^r)$
2	150	250	187.5	2531.25
4	150	250	187.5	2031.25
6	150	250	187.5	1501.25
8	150	130	187.5	1061.25

Table 4
Numerical results with different government subsidy

a	q^0	$\Pi(q^0)$	q_a	$\Pi(q^a)$	κ
0.5	130	1061.25	150	1156.25	8.95
1	130	1061.25	170	1261.25	18.85
1.5	130	1061.25	190	1376.25	29.68
2	130	1061.25	150	1501.25	41.46

5.1. Value of recycling supply mode

We first explore the order quantity and expected profit of the classical single inventory system with and without remanufactured (recycling) supplier. Note that the single sourcing system with one more recycling supplier equals a dual sourcing system. We set the basic parameters sets in inventory systems as in Table 2

Varying the order cost from the recycling supplier c_r and keeping the other parameters fixed, we can get the optimal profit and order quantity for the retailer. Summarize the results and present it in Table 3.

From Table 3, we can observe that when there is only one supplier in the system, the optimal expected profit is always lower than the systems with recycling supplier. And as the order cost of the retailer from the recycling supplier c_r is increasing, the optimal retailer's expected profit will decrease. We claim that the used products through recycling and remanufacturing, then are sold to the retailer, which are not only beneficial to environmental protection but also making the retailer's expected profit increase.

5.2. Value of government subsidy

In this section, we study a system with two suppliers in the market and one of these two suppliers provides environmental protection products to the retailer, and the government provides a subsidy to such supplier to encourage his environmental protection act. We investigate the retailer's optimal expected profit and order quantity. Define $\kappa = \frac{\Pi(q^a) - \Pi(q^0)}{\Pi(q^0)} \cdot 100\%$, where q^0 is the optimal order quantity and $\Pi(q^0)$ is the optimal retailer's expected profit without government subsidy. κ represents the difference of the optimal retailer's expected profits between the systems with and without government subsidy. We present the numerical results in Table 4.

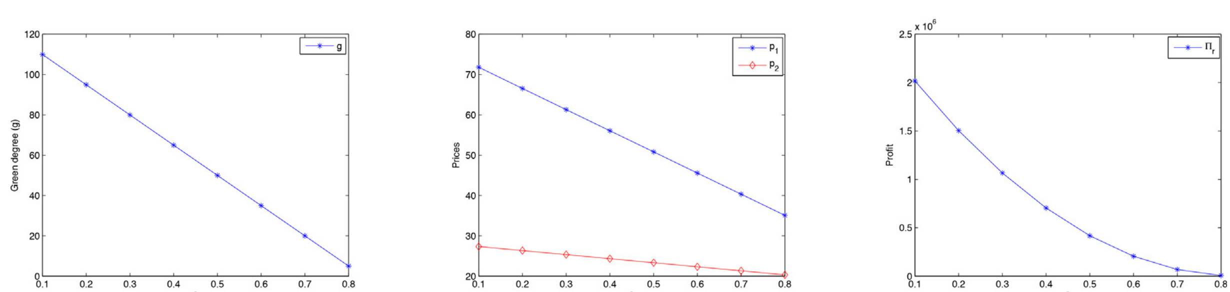
Table 4 indicates that as the government subsidy increases, the retailer's optimal expected profits will increase. In reality, the recycling supplier's subsidy received from the government sometimes transfer to the retailer, to appeal retailer orders more products from recycling channel. Obviously, the government subsidy can promote environmental protection and increase the retailer's expected profits.

In Sections 5.1 and 5.2, we explore the value of the recycling supplier and the value of the government subsidy based on inventory perspective, respectively. In the next section, we investigate the retailer's pricing decision under the condition where the customers are assumed to be sensitive to the products' green degree.

5.3. Price and green degree decisions

We conduct a numerical example to derive the optimal green degree of product 1 and analyze the impacts of the green degree on the pricing decisions of two different products and the retailer's optimal profit. The basic parameters we used as follows: $\theta = 0.5$, $a = 1000$, $b_1 = 20$, $b_2 = 20$, $\alpha = 0.5$, $n = 5$, $k_1 = 10$, $k_2 = 5$, $c_0 = 20$. We explore the impacts of system parameters θ and α on the optimal green degree and the optimal pricing decisions for two different products. The results are listed in Figs. 2 and 3. Fig. 2(a) shows that as θ (the loyalty to the product from supplier 1) increases, the optimal green degree will decrease. The reason is that although the base demand increases as θ increases, the Supplier 1 do not increase the green degree to appeal more demand whereas reduce the products' green degree to lower the production cost. In Fig. 2(b), counter-intuitively, we can see that the optimal prices for two different products are all decreasing with the loyalty to Supplier 1 channel θ is increasing. The reason is that the demands from the two suppliers are not only affected by the prices of two products but also depend on the green degree of green product. As θ increases, green degree g is decreasing, thus the price of product 1 is decreasing, even the green product's loyalty θ increases. Price of product 2 decreases slowly, this is because of the simultaneous influences of the loyalty to green product θ and cross-effect of green degree g. Fig. 2(c) shows that the retailer's optimal profit will significantly decrease as θ is increasing. Indeed, green products can promote environmental protection, but the development of green products is costly. We should work together to protect the environment and share costs.

Fig. 3 investigate the sensitivity coefficient to green degree of



(a) (b) (c)

Fig. 2. (a) Optimal green degree of supplier 1. (b) Optimal prices for two products. (c) The optimal profits for retailer.

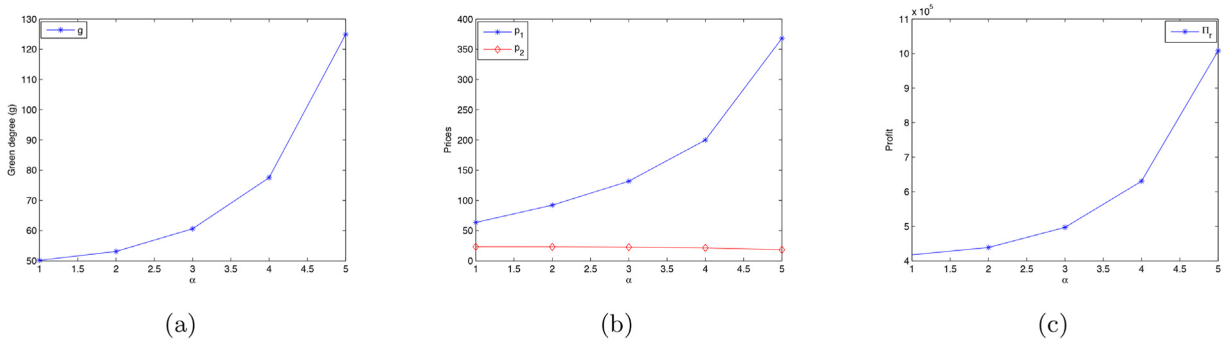


Fig. 3. (a) Optimal green degree of supplier 1. (b) Optimal prices for two products. (c) The optimal profits for retailer.

production cost, i.e., α, which means when the green degree of product 1 increases one unit, the production cost of product 1 will increase α units. Fig. 3(a) shows the optimal green degree is increasing as α increases. This is counter-intuitive. We can explain as follows: as α increases, the production cost of product 1 will increase, this will decrease g. The increase of green degree g will cause demand increase, thereby affect the profit of the retailer, thus the final comprehensive result is the green degree g is increasing with α is increasing, this leads to the profit increase of supplier 1. Also, the optimal price of product 1 will increase significantly, as shown in Fig. 3(b) and the price of product 2 change slowly. Fig. 3(c) indicates the optimal profit of retailer is increasing as α increases, thus the retailer should order more green product no matter how expensive it is, as long as the customers in the market are environmental sensitive.

6. Conclusions

This paper studies the green growth problems for companies based on inventory and supply chain system. We consider single period inventory model with recycling action and the government subsidy for one and two supply options systems, respectively. We give the optimal order decisions for the retailer under the different green growth action under the assumption that customers believe two supply channel provide the same products. In reality, customers are sensitive to the green product. Thus, we consider the retailer's optimal pricing strategies and the optimal green degree decision for "green" supplier under the supply chain perspective. Inventory and pricing are important for companies to make decisions.

We can derive the retailer's optimal order quantity by newsvendor fractile. When considering the recycling supplier, the order decision relies on the cost difference between the two supply options. The larger the cost difference, the more orders are placed through recycling supplier. Government subsidy is a green growth mechanism, which can stimulate companies to use environmentally friendly products. Green degree of product, in turn, affect the demand of environmental sensitive customers and the supplier should decide the quote green degree.

This work contributes more insights not only on economic criteria but environmental concerns. For example, which provides a guild for firms on how much to order from various supply channel and how much the price to sell to the customers as to different products. Some other directions are worth pursuing in future research. First, we derive the inventory and pricing policy separately, how about the decision for companies jointly consider the inventory and pricing? Second, all decisions are derived in a single period, what happens for the companies if the model is extended to multi-period? Third, some other green growth mechanism, such as carbon emission, could be studied in future work.

Acknowledgement

This work was supported by the National Natural Science Foundation of China under grant 71571173.

References

Absi, N., Dauzère-Pérès, S., Kedad-Sidhoum, S., Penz, B., Rapine, C., 2013. Lot sizing with carbon emission constraints. Eur. J. Oper. Res. 227 (1), 55–61.
Arıkan, E., Jammernegg, W., 2014. The single period inventory model under dual sourcing and product carbon footprint constraint. Int. J. Prod. Econ. 157, 15–23.
Bouchery, Y., Ghaffari, A., Jemai, Z., Dallery, Y., 2012. Including sustainability criteria into inventory models. Eur. J. Oper. Res. 222 (2), 229–240.
Carvalho, H., Govindan, K., Azevedo, S.G., Cruz-Machado, V., 2017. Modelling green and lean supply chains: An eco-efficiency perspective. Resources. Conserv. Recycl. 120, 75–87.
Castillo, V.E., Mollenkopf, D.A., Bell, J.E., Bozdogan, H., 2018. Supply chain integrity: A key to sustainable supply chain management. J. Bus. Logistics 39 (1), 38–56.
Chen, X., Benjaafar, S., Elomri, A., 2013. The carbon-constrained eoq. Oper. Res. Lett. 41 (2), 172–179.
Choi, S.C., 1996. Price competition in a duopoly common retailer channel. J. Retail. 72 (2), 117–134.
Coskun, S., Ozgur, L., Polat, O., Gungor, A., 2016. A model proposal for green supply chain network design based on consumer segmentation. J. Cleaner Prod. 110, 149–157.
Ding, H., Liu, Q., Zheng, L., 2016. Assessing the economic performance of an environmental sustainable supply chain in reducing environmental externalities. Eur. J. Oper. Res. 255 (2), 463–480.
El Saadany, A.M., Jaber, M.Y., 2010. A production/remanufacturing inventory model with price and quality dependant return rate. Comput. Indus. Eng. 58 (3), 352–362.
Fahimnia, B., Tang, C.S., Davarzani, H., Sarkis, J., 2015. Quantitative models for managing supply chain risks: A review. Eur. J. Oper. Res. 247 (1), 1–15.
Ghadimi, P., Wang, C., Lim, M.K., 2019. Sustainable supply chain modeling and analysis: Past debate, present problems and future challenges. Resour. Conserv. Recycl. 140, 72–84.
Govindan, K., Kaliyan, M., Kannan, D., Haq, A.N., 2014. Barriers analysis for green supply chain management implementation in Indian industries using analytic hierarchy process. Int. J. Prod. Econ. 147, 555–568.
Guide Jr., V.D.R., Jayaraman, V., Linton, J.D., 2003. Building contingency planning for closed-loop supply chains with product recovery. J. Oper. Manag. 21 (3), 259–279.
Guide Jr., V.D.R., Jayaraman, V., Srivastava, R., Benton, W., 2000. Supply-chain management for recoverable manufacturing systems. Interfaces 30 (3), 125–142.
Gunasekaran, A., Subramanian, N., Rahman, S., 2015. Green supply chain collaboration and incentives: Current trends and future directions.
Hua, G., Cheng, T., Wang, S., 2011. Managing carbon footprints in inventory management. Int. J. Prod. Econ. 132 (2), 178–185.
Jaber, M.Y., Glock, C.H., El Saadany, A.M., 2013. Supply chain coordination with emissions reduction incentives. Int. J. Prod. Res. 51 (1), 69–82.
Khouja, M., 1996. A note on the newsboy problem with an emergency supply option. J. Oper. Res. Soc. 47 (12), 1530–1534.
Klosterhalfen, S., Kiesmüller, G., Minner, S., 2011. A comparison of the constant-order and dual-index policy for dual sourcing. Int. J. Prod. Econ. 133 (1), 302–311.
Kurata, H., Yao, D.-Q., Liu, J.J., 2007. Pricing policies under direct vs. indirect channel competition and national vs. store brand competition. Eur. J. Oper. Res. 180 (1), 262–281.
Li, B., Zhu, M., Jiang, Y., Li, Z., 2016. Pricing policies of a competitive dual-channel green supply chain. J. Cleaner Prod. 112, 2029–2042.
Ma, W.-m., Zhao, Z., Ke, H., 2013. Dual-channel closed-loop supply chain with government consumption-subsidy. Eur. J. Oper. Res. 226 (2), 221–227.
Mahadevan, B., Pyke, D.F., Fleischmann, M., 2003. Periodic review, push inventory policies for remanufacturing. Eur. J. Oper. Res. 151 (3), 536–551.
Mallidis, I., Dekker, R., Vlachos, D., 2012. The impact of greening on supply chain design and cost: a case for a developing region. J. Transport Geogr. 22, 118–128.
McGuire, T.W., Staelin, R., 1983. An industry equilibrium analysis of downstream vertical integration. Marketing Sci. 2 (2), 161–191.
Nagurney, A., Liu, Z., Woolley, T., 2007. Sustainable supply chain and transportation networks. Int. J. Sustain. Transport. 1 (1), 29–51.
Rosič, H., Jammernegg, W., 2013. The economic and environmental performance of dual sourcing: A newsvendor approach. Int. J. Prod. Econ. 143 (1), 109–119.
Roy, A., Maity, K., Maiti, M., et al., 2009. A production-inventory model with remanufacturing for defective and usable items in fuzzy-environment. Comput. Indus.

Eng. 56 (1), 87–96.
Savaskan, R.C., Bhattacharya, S., Van Wassenhove, L.N., 2004. Closed-loop supply chain models with product remanufacturing. Manage. Sci. 50 (2), 239–252.
Sheu, J.-B., Chen, Y.J., 2012. Impact of government financial intervention on competition among green supply chains. Int. J. Prod. Econ. 138 (1), 201–213.
Song, J., Leng, M., 2012. Analysis of the single-period problem under carbon emissions policies, Handbook of newsvendor problems. Springer, pp. 297–313.
Song, M., Peng, J., Wang, J., Dong, L., 2018. Better resource management: An improved resource and environmental efficiency evaluation approach that considers undesirable outputs. Resources. Conserv. Recycl. 128, 197–205.
Tseng, M.-L., Islam, M.S., Karia, N., Fauzi, F.A., Afrin, S., 2019. A literature review on green supply chain management: Trends and future challenges. Resources. Conserv. Recycl. 141, 145–162.
Tseng, M.-L., Lim, M., Wu, K.-J., Zhou, L., Bui, D.T.D., 2018. A novel approach for enhancing green supply chain management using converged interval-valued triangular fuzzy numbers-grey relation analysis. Resources. Conserv. Recycl. 128, 122–133.
Van Der Laan, E., 1997. The effects of remanufacturing on inventory control.
Van Der Laan, E., Salomon, M., Dekker, R., Van Wassenhove, L., 1999. Inventory control in hybrid systems with remanufacturing. Manage. Sci. 45 (5), 733–747.
Winslow, K.M., Laux, S.J., Townsend, T.G., 2018. A review on the growing concern and potential management strategies of waste lithium-ion batteries. Resources. Conserv. Recycl. 129, 263–277.
Xu, L., Wang, C., 2018. Sustainable manufacturing in a closed-loop supply chain considering emission reduction and remanufacturing. Resources. Conserv. Recycl. 131, 297–304.
Yang, L., Wang, J., Shi, J., 2017. Can china meet its 2020 economic growth and carbon emissions reduction targets? J. Cleaner Prod. 142, 993–1001.
Yang, L., Wang, K.-L., Geng, J.-C., 2018. China's regional ecological energy efficiency and energy saving and pollution abatement potentials: An empirical analysis using epsilon-based measure model. J. Cleaner Prod. 194, 300–308.
Zhao, S., Zhu, Q., Cui, L., 2018. A decision-making model for remanufacturers: Considering both consumers environmental preference and the government subsidy policy. Resources. Conserv. Recycl. 128, 176–186.
Zhu, W., He, Y., 2017. Green product design in supply chains under competition. Eur. J. Oper. Res. 258 (1), 165–180.