RAIRO-Oper. Res. 53 (2019) 609–626
https://doi.org/10.1051/ro/2017061

RAIRO Operations Research
www.rairo-ro.org

OPTIMAL PRODUCT QUALITY AND PRICING STRATEGY FOR A TWO-PERIOD CLOSED-LOOP SUPPLY CHAIN WITH RETAILER VARIABLE MARKUP

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Abstract. In this paper, we consider a two-period closed-loop supply chain which is comprised of a single manufacturer and a single retailer for trading a single product. At the retailer, the demand in the first period depends on the selling price, product quality and refund price, whereas in the second period, it depends on the selling price and the product quality. The retailer sets the selling prices with variable markups on the wholesale prices of the manufacturer and offers a return policy (immediate return and used product return) limited to the first period only. The immediate return is dependent on the refund price and the product quality, and the amount of returned used items is a fraction of the first period's demand. The retailer sends the returned items to the manufacturer who reproduces/repairs those items and sells in the second period. We assume that the manufacturer acts as the Stackelberg leader and the retailer as the follower. We study the impacts of return policy, product quality and pricing strategy on the optimal decisions under two decision strategies (I and II). In the decision strategy I, both the players optimize their total profits over the entire selling season, whereas in the decision strategy II, they optimize each period's profit sequentially. With the help of a numerical example we explore that the decision strategy I gives better result than the decision strategy II in terms of all decision variables except the product quality. We also investigate the effects of key model-parameters on the optimal decisions.

Mathematics Subject Classification. 90B05, 90B06.

Received February 24, 2017. Accepted September 7, 2017.

1. Introduction

With the rapid development of economy and society, people's appeal of saving energy and sustainable development is increasing. As a research hotspot, the study of closed-loop supply chain management, which explicitly takes account of product returns, in addition to the downstream flow of materials, plays an increasing prominent role in sustainable development and environment protection. The economical and environmental benefits of product remanufacturing have been widely recognized during the past fifteen years [6,18,37]. A closed-loop supply chain (CLSC) consists of both forward and reverse activities. Forward activities include new product development, product design and engineering, procurement and production, marketing, sales, distribution, and

Keywords. Closed-loop supply chain, retailer variable markup, two-period model, remanufacturing, return policy, product quality, pricing strategy.

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after-sale service, while reverse activities refer to all those needed to close the loop, such as product acquisition, reverse logistics, points of use and disposal, testing, sorting, refurbishing, recovery, recycling, remarketing, and reselling [6,8]. The aim of remanufacturing is "to bring the worn-out or used products into like-new conditions by carrying out the necessary disassembly, overhaul, and replacement operations" [29]. So there is a process of recapturing the value added to the material during the manufacturing stage. However, in the CLSC, the manufacturer not only sells the original product to consumers through forward channel but also can collect the used product through the retailer for remanufacturing and recycling *via* reverse channel. Compared with the traditional forward supply chain, the closed-loop supply chain could reduce environment pollution, improve the utilization rate of resources, and extend the service life of the products and minimize the resource consumption and environmental influence on sustainable development. It also reduces greenhouse gas emission. Therefore, it attracts extensive attention from academia and enterprises. Many attempts have been made in developed countries to control electronic wastes such as Waste of Electric and Electronic Equipment (WEEE) directives, implemented in most European countries since 2003, RoHS in United States, 2003, and Extended Producer Responsibility (EPR) issued by OECD in 1984. Also, many manufacturers such as IBM, Ford, Ceterpillar, Muji and Timberland all have established economically viable remanufacturing systems either by themselves or *via* third party [9,17,34].

In CLSC, the choice of an appropriate reverse channel structure and return policy are required at the time of remanufacturing to obtain the maximum profit. Generally, there are several ways to collect the used products, which vary across industries and stores. Savaskan *et al.* [28] analyzed the problem of choosing appropriate reverse channel structure for collecting used products from end customer. Shi *et al.* [30] assumed that the manufactured (new) and remanufactured products are sold in the same market at the same price. Ahmed *et al.* [2] assumed that demand for manufactured products is different from that for remanufactured ones. Jayaraman *et al.* [10] proved that remanufacturing of used products can not only improve the utilization of resources and create a favorable social image but also can yield extra profit and enhance competitiveness. Return issues have become even more significant over the past two decades especially due to the Internet which gave birth to e-commerce and e-marketplaces. This is because consumers cannot often have a chance to physically investigate a product before their purchasing decision [22]. A survey shows that more than 70% of consumers consider a return policy before the buying decision [23]. The return policy may be defined in terms of selling price, product quality and refund price. It may also include short time limit for returning the products. Notable e-tail enterprises Amazon.com and Crutchfied.com accept returns on most items within 30 days and pay for return shipping only for their own mistakes. A generous return policy can increase the forward sales flow by enhancing consumers' buying intention. It can also increase the return flow and related reverse logistics costs.

As the consumers often do not have enough information about the true quality of a product, purchase decision is closely related to return policy. It pertains not only to defect problems related to conformance quality but also to consumer dissatisfaction with design quality of a product related to the specifications or characteristics of a product that fulfill consumers' needs and preferences [11]. A survey of Hewlett-Packard printers by Guide *et al.* [12] also shows that 40% of the returns pertain to product performance not meeting the consumers' expectations, while 20% of the returns are related to conformance quality problems. Thus, we use the term "quality" to refer to overall aspects of quality, including both design and conformance. High quality products and services can satisfy the customers, reduce the number of returns, deserve high selling prices because higher prices signal better quality, while low quality products and services lead to frequent return [15,32]. When demand is price-sensitive, the high quality and services deserve high selling prices which lead to decrease customer demand. If the customers are not worried about the selling prices but much concerned about the product quality, then the manufacturer adopts "high price, high quality" policy by improving quality.

In CLSC, it is very important to decide the price of the product and the collecting price of used items. Ray *et al.* [27] studied the optimal pricing/trade-in strategies for the durable, remanufacturable products. Gu *et al.* [13], Wang *et al.* [33] and Ge and Huang [14] all used supply chain system pricing strategy which is the interaction of game theory with supply chain and reverse supply chain. There are several studies that focused on pricing of remanufactured products, but many of them have not considered the whole supply chain. Our study will be focused on pricing decisions in a closed-loop supply chain involving manufacturer, retailer and potential customers. The pricing policy may be initiated in two different ways. The players may either (a) announce all the prices (wholesale prices, selling prices and refund price) at the beginning of the selling season (pre-announced pricing [19, 31]) or (b) announce only the prices of the first-period, and wait for the beginning of the second period to announce the second-period's price (responsive pricing [3]). Pre-announced pricing is commonly used in practice indirectly. For instance, firms may set a regular price and offer introductory price-cuts (*via* promotional offers or coupons) or charge introductory price premiums. Under responsive pricing strategy, a firm can influence the demand for its output by setting prices according to the actual demand conditions and the available capacity. Examples of such products include high-tech consumer electronics (smart-phone, tablet, computer), media items (movie, book), and digital products (computer software, smart-phone apps). Under these circumstances, we explore two strategies to differentiate the pre-announced (Strategy I) and responsive pricing (Strategy II).

This paper explores a CLSC with one manufacturer and one retailer in which the manufacturer decides the wholesale prices and the product quality, while the retailer chooses the selling prices through RVM [25] and refund price. Two different decision strategies are established to answer the following questions:

(1) What are the optimal return policy, product quality and pricing strategy in both the decision strategies?
(2) How does the retailer's optimal return policy affect the customer's demand and return decisions? Given that customer's immediate returns are sensitive to the refund price as well as the product quality and used product returns are dependent on the demand in the first period.
(3) How does the optimal return decision affect the customer purchase decisions? Given that the customer demand in the first period is dependent on the refund price, the selling price and the product quality while that in the second period is sensitive to the selling price and the product quality but not to the refund price.
(4) How does the manufacturer manage the reverse supply chain when the returned products (immediate return and used product return) during the first period are reproduced/repaired and ready to sell in the second period? Given that the returned products are sold only in the second period with the newly produced ones and with the same quality level.
(5) Which decision strategy gives the best optimal solution of the supply chain? Given that the manufacturer is the Stackelberg leader and the retailer is the follower in both the decision strategies.

The rest of the paper is organized as follows: The next section describes the notation and assumptions used in this paper. Section 3 deals with model formulation and analysis. Numerical results are given in Section 4. Section 5 investigates the sensitivity of some key-parameters and Section 6 concludes the paper with the future research directions.

2. Notations and assumptions

The following notations are used for developing the proposed model:

D_1 demand rate at the retailer in the first period.
D_2 demand rate at the retailer in the second period.
D_r return quantity during the first period.
D_u used product returned during the first period.
d_1 basic demand at the retailer in the first period.
d_2 basic demand at the retailer in the second period.
ϕ basic return quantity.
τ a fraction, $0 < \tau < 1$.
p_1 selling price of the retailer in the first period.
p_2 selling price of the retailer in the second period.
λ_1 retailer's variable markup in the first period.
λ_2 retailer's variable markup in the second period.
w_1 wholesale price of the manufacturer in the first period.

w_2	wholesale price of the manufacturer in the second period.
q	product quality maintained by the manufacturer.
$r(< p_1)$	refund price per unit of returned item.
c	production cost per unit of newly produced item.
$c_r(< c)$	production cost per unit of reproduced/repaired item.
A_1	price paid by the manufacturer to the retailer for every unit of usual return product.
A_2	price paid by the manufacturer to the retailer for every unit of used product return.
B	price paid by the retailer to the customers for every unit of used product return.
H	effect cost for each returned product.
g	goodwill lost cost for totally impure product.
Π_m	profit of the manufacturer.
Π_r	profit of the retailer.
Π	profit of the whole system.

The following assumptions are made to develop the proposed model:

(1) We consider a closed-loop supply chain which consists of a single manufacturer and a single retailer. The manufacturer produces an item with a certain quality (q) and sells it to the potential customers through a retailer. During the first selling period, the customers may return the product immediately due to some major defect/error or under-quality reason and some customers may return the product after use (end of life). In the first period, the retailer accepts the returned items and refunds money (r per unit). However, in the second period, the retailer does not entertain any return and refund policy. The retailer delivers the returned items to the manufacturer who repairs/reproduces those items so that the quality remains the same as the newly produced ones. The reproduced items are sold in the second period with newly produced ones.

(2) In the first period, the demand rate of the retailer depends on the selling price of the current period, refund price and the product quality. We take $D_1 = d_1 - \alpha_1 p_1 + \beta_1 q + \gamma r$, where α_1, β_1 and γ are positive constants so that the demand is always positive. The return policy with a higher refund price may lead to higher market demand whereas a higher selling price has a negative impact on the demand [5, 20, 24, 26, 36]. If customers have the tendency to buy high quality product, they have to pay higher price. In the first period, the return rate is dependent on the refund price and the product quality. We take $D_r = \phi + \eta r - \rho q$, where η and ρ are positive constants such that the return rate is non-negative [20, 35]. The return rate of the used product is taken as a fraction of demand rate in the first period. We take $D_u = \tau D_1$. A higher return compensation has a positive impact on the return quantity. It is quite natural that if the product quality is high, then the return rate would be low. We assume that the demand rate in the second period is dependent on the selling price and the product quality. We take $D_2 = d_2 - \alpha_2 p_2 + \beta_2 q$ where α_2 and β_2 are positive constants such that the demand is always positive. These forms of demand and return function indicate that, it is a challenging task for the manufacturer and the retailer to produce units in suitable quality and set a reasonable selling price.

(3) The manufacturer is the Stackelberg leader and the retailer is the follower. First, the manufacturer declares wholesale prices, product quality and then the retailer sets his selling prices through RVM and refund price for the two periods under two different decision strategies.

(4) The manufacturer reproduces the returned items at a cost c_r which is less than the production cost c.

(5) The selling prices p_1 and p_2 are taken as variable markups on wholesale prices *i.e.* $p_1 = (1 + \lambda_1)w_1$ and $p_2 = (1 + \lambda_2)w_2$.

(6) Lead time is zero.

3. Model development and analysis

The CLSC has a forward supply channel where the manufacturer produces the product and sells it to the potential customers through the retailer. In this paper, we consider that the manufacturer divides his/her selling

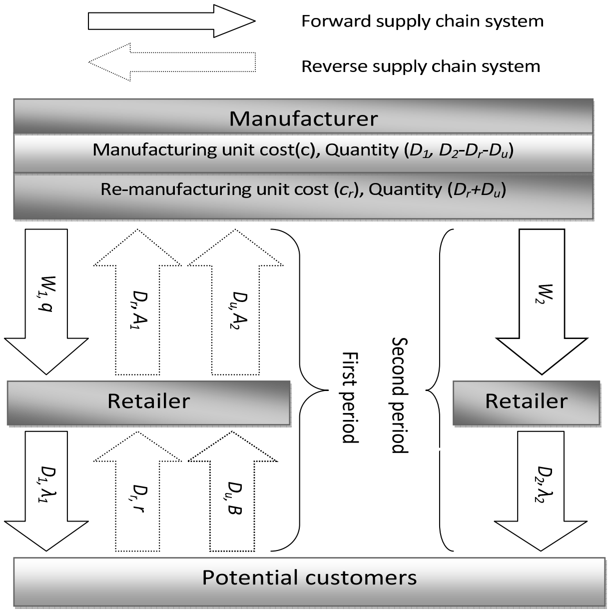


Figure 1. Graphical representation of the closed loop supply chain.

season into two consecutive periods. In the first period, the retailer follows two types of return policy: immediate return and used product return. In the first policy, the return is dependent on the refund price and the product quality while in the second policy, the return is a fraction of the first period's demand. However, in the second period, the retailer does not accept any return from the customers (see Fig. 1). Firstly, the manufacturer declares his wholesale prices w_1 and w_2 and product quality q. Then the retailer sets the refund price r per unit item for the first period only and the selling prices which are taken as the retail variable markup (RVM) for the two periods. After collection, the returned items are disassembled and inspected carefully, and immediately returned items are reused while used items are repaired. The manufacturer needs to maintain product quality by controlling the failure rate at the manufacturing stage as well as product delivery and service quality (speed and careless) in the sales stage. For this, we consider a cost component Gq^2, (where $G(>0)$, the quality improvement effort cost, is a scalar parameter) for each period which is a continuously differentiable convex function [4, 21]. For production of impure items, the manufacturer incurs a goodwill lost cost $(1-q)g$, where $(1-q)$ is the impurity fraction. In addition, we ignore those costs such as set-up cost, ordering cost and transportation cost that have no direct effect on the optimal decisions.

We consider Π_{m1}, Π_{m2} and Π_m as the manufacturer's profits in the first period, second period and the entire selling season, respectively. Then we have

$$\Pi_{m1}(w_1, q) = (w_1 - c)D_1 - A_1 D_r - A_2 D_u - Gq^2 - (1-q)g \tag{3.1}$$

$$\Pi_{m2}(w_2, q) = (w_2 - c)(D_2 - D_r - D_u) + (w_2 - c_r)(D_r + D_u) - Gq^2 - (1-q)g \tag{3.2}$$

and

$$\Pi_m(w_1, w_2, q) = \Pi_{m1}(w_1, q) + \Pi_{m2}(w_2, q) \tag{3.3}$$

In the first period, there are sales profit, refund price paid due to usual return and used product return, product quality maintenance cost and goodwill lost cost while in the second period, there are sales profits from the newly produced products and repaired/reproduced products, cost due to quality maintenance and goodwill lost cost.

In this similar way, we consider Π_{r1}, Π_{r2} and Π_r as the retailer's profits in the first period, second period and the entire selling season, respectively. Then we have

$$\Pi_{r1}(\lambda_1, r) = (p_1 - w_1)D_1 + (A_1 - r)D_r + (A_2 - B)D_u - H\tau^2, \tag{3.4}$$

$$\Pi_{r2}(\lambda_2) = (p_2 - w_2)D_2, \tag{3.5}$$

and $$\Pi_r(\lambda_1, \lambda_2, r) = \Pi_{r1}(\lambda_1, r) + \Pi_{r2}(\lambda_2), \tag{3.6}$$

where λ_1 and λ_2 are given by

$$p_1 = (1 + \lambda_1)w_1,$$
$$p_2 = (1 + \lambda_2)w_2.$$

Therefore, the whole system's profit is given by

$$\Pi(w_1, w_2, q, \lambda_1, \lambda_2, r) = \Pi_m(w_1, w_2, q) + \Pi_r(\lambda_1, \lambda_2, r). \tag{3.7}$$

With these profit functions, we now discuss two different decision strategies which are described below:

3.1. Decision strategy I

In this decision strategy, the decisions for both periods are made by each player at the beginning of the first period. Under this assumption, the manufacturer optimizes his total profit for the entire selling season and declares his wholesale prices (w_1^I and w_2^I) and the product quality (q^I). Then the retailer sets his selling prices (p_1^I and p_2^I) through variable markups (λ_1^I and λ_2^I), and the refund price (r^I). Such a decision strategy can be applied in certain food industry, dairy industry and pharmaceutical industry where the manufacturers can announce their prices if there are not much changes in their products. The retailer optimizes $\Pi_r(\lambda_1, \lambda_2, r)$ with respect to λ_1, λ_2 and r and gives his reaction as

$$\lambda_1 = \frac{\Big(2\eta(d_1 - w_1\alpha_1 + \beta_1 q) - \gamma(\phi - \rho q - \eta A_1) + \gamma^2\tau(A_2 - B) - 2\tau\eta\alpha_1(A_2 - B)\Big)}{w_1(4\alpha_1\eta - \gamma^2)},$$

$$\lambda_2 = \frac{(d_2 - w_2\alpha_2 + q\beta_2)}{2\alpha_2 w_2},$$

$$r = \frac{\Big(\gamma(d_1 - w_1\alpha_1 + \beta_1 q) - 2\alpha_1(\phi - \rho q - \eta A_1) + \gamma\tau\alpha_1(A_2 - B)\Big)}{w_1(4\alpha_1\eta - \gamma^2)}.$$

We obtain the values of λ_1, λ_2 and r by setting the first order partial derivatives $\frac{\partial \Pi_r}{\partial \lambda_1}, \frac{\partial \Pi_r}{\partial \lambda_2}$ and $\frac{\partial \Pi_r}{\partial r}$ each equal to zero. The second order sufficient condition can be obtained from the Hessian matrix:

$$H_r^I = \begin{pmatrix} \frac{\partial^2 \Pi_r}{\partial \lambda_1^2} & \frac{\partial^2 \Pi_r}{\partial \lambda_1 \partial \lambda_2} & \frac{\partial^2 \Pi_r}{\partial \lambda_1 \partial r} \\ \frac{\partial^2 \Pi_r}{\partial \lambda_2 \partial \lambda_1} & \frac{\partial^2 \Pi_r}{\partial \lambda_2^2} & \frac{\partial^2 \Pi_r}{\partial \lambda_2 \partial r} \\ \frac{\partial^2 \Pi_r}{\partial r \partial \lambda_1} & \frac{\partial^2 \Pi_r}{\partial r \partial \lambda_2} & \frac{\partial^2 \Pi_r}{\partial r^2} \end{pmatrix} = \begin{pmatrix} -2\alpha_1 w_1^2 & 0 & \gamma w_1 \\ 0 & -2\alpha_2 w_2^2 & 0 \\ \gamma w_1 & 0 & -2\eta \end{pmatrix}.$$

Here $|H_{r2}^I| = 4\alpha_1\alpha_2 w_1^2 w_2^2 > 0$, and also $|H_r^I| = 2\alpha_2 w_1^2 w_2^2(\gamma^2 - 4\alpha_1\eta)$. Obviously H_r^I is negative definite if $\eta > \frac{\gamma^2}{4\alpha_1}$.

After getting the reaction from the retailer, the manufacturer maximizes his total profit function $\Pi_m(w_1, w_2, q)$.

The associated Hessian matrix is given by

$$H_m^I = \begin{pmatrix} \frac{\partial^2 \Pi_m}{\partial w_1^2} & \frac{\partial^2 \Pi_m}{\partial w_1 \partial w_2} & \frac{\partial^2 \Pi_m}{\partial w_1 \partial q} \\ \frac{\partial^2 \Pi_m}{\partial w_2 \partial w_1} & \frac{\partial^2 \Pi_m}{\partial w_2^2} & \frac{\partial^2 \Pi_m}{\partial w_2 \partial q} \\ \frac{\partial^2 \Pi_m}{\partial q \partial w_1} & \frac{\partial^2 \Pi_m}{\partial q \partial w_2} & \frac{\partial^2 \Pi_m}{\partial q^2} \end{pmatrix} = \begin{pmatrix} \frac{-4\alpha_1^2\eta}{4\alpha_1\eta-\gamma^2} & 0 & \frac{\alpha_1(2\beta_1\eta+\gamma\rho)}{4\alpha_1\eta-\gamma^2} \\ 0 & -2\alpha_2 & \frac{\beta_2}{2} \\ \frac{\alpha_1(2\beta_1\eta+\gamma\rho)}{4\alpha_1\eta-\gamma^2} & \frac{\beta_2}{2} & -4G \end{pmatrix}.$$

Here $|H_{m2}^I| = \frac{8\alpha_1^2\alpha_2\eta}{4\alpha_1\eta-\gamma^2} > 0$. Obviously H_m^I is negative definite if $G > \frac{1}{16\alpha_2}\Big[\beta_2^2 + \frac{\alpha_2(2\beta_1\eta+\gamma\rho)^2}{(4\alpha_1\eta-\gamma^2)\eta}\Big]$. Then using the first order conditions for optimality *i.e.* setting $\frac{\partial \Pi_m}{\partial w_1}, \frac{\partial \Pi_m}{\partial w_2}$ and $\frac{\partial \Pi_m}{\partial q}$ each equal to zero, the equilibrium solution can be obtained as given in the following proposition:

Proposition 3.1. *At the equilibrium, under decision strategy I, the manufacture's wholesale prices, product quality and the retailer's variable markups and refund price are given respectively by*

$$\begin{aligned}
w_1^I &= \frac{1}{4\alpha_1\eta}\Big[U + \Big((2\beta_1\eta+\gamma\rho)\big((8g\alpha_2+d_2\beta_2)\eta(\gamma^2-4\alpha_1\eta) + \alpha_2(\eta Y + c\eta(-\beta_2(\gamma^2-4\alpha_1\eta)+Z) \\
&\quad + \gamma(2\beta_1\eta+\gamma\rho)\phi)\Big)X^{-1}\Big], \\
w_2^I &= \Big[d_2\big(16G\eta(\gamma^2-4\alpha_1\eta) + (2\beta_1\eta+\gamma\rho)^2\big) + \beta_2\eta\big(8g(\gamma^2-4\alpha_1\eta)+Y\big) + c(X+\beta_2\eta Z)) \\
&\quad + \beta_2\gamma(2\beta_1\eta+\gamma\rho)\phi\Big]\Big[2X\Big]^{-1}, \\
q^I &= VX^{-1}, \\
\lambda_1^I &= -\Big[2\alpha_1\eta\Big((8g\alpha_2+d_2\beta_2)2\beta_1\eta^2 + (16G\alpha_2-\beta_2^2)(2d_1-c_r\gamma)\eta^2(8g\alpha_2+d_2\beta_2)\gamma\eta\rho + 2\alpha_2\eta\rho(A_1+c_r) \\
&\quad (2\beta_1\eta+\gamma\rho) - c\eta\Big(\alpha_2(\beta_2+2\rho)(2\beta_1\eta+\gamma\rho) - (16G\alpha_2-\beta_2^2)\eta(\gamma+2\alpha_1(-1+\tau))\Big) + 2\gamma^2\eta\tau \\
&\quad (16G\alpha_2-\beta_2^2)(A_2+B) + 8\alpha_2\beta_1\eta\tau(A_2-B)(\gamma\rho+\beta_1\eta) - 2\alpha_1\eta^2\tau(4A_2-3B+c_r)(16G\alpha_2-\beta_2^2) \\
&\quad + 2\alpha_2\gamma^2\rho^2\tau(A_2-B) + (-16G\alpha_2+\beta_2^2)\gamma\eta\phi\Big)\Big] \times X \times \Big[X^2 + \Big\{U + \Big((2\beta_1\eta+\gamma\rho)V\Big)\Big\}\Big]^{-1}, \\
\lambda_2^I &= \frac{1}{2} - cX\Big[d_2(16G\eta(\gamma^2-4\alpha_1\eta) + (2\beta_1\eta+\gamma\rho)^2) + \beta_2\eta(8g(\gamma^2-4\alpha_1\eta)+Y) + c\Big(X+\beta_2\eta Z)\Big) \\
&\quad + \beta_2\gamma(2\beta_1\eta+\gamma\rho)\phi\Big]^{-1}
\end{aligned}$$

and

$$\begin{aligned}
r^I &= \Big[-2\beta_1\gamma\eta(8g\alpha_2+d_2\beta_2) + \gamma^2\eta(16G\alpha_2-\beta_2^2)(A_1+c_r) - 8A_1\alpha_1\eta^2(16G\alpha_2-\beta_2^2) + \rho(8g\alpha_2 \\
&\quad + d_2\beta_2)(\gamma^2-8\alpha_1\eta) + 4A_1\alpha_2\beta_1\eta(2\beta_1\eta+\gamma\rho) + 4\alpha_2\rho^2(A_1+c_r)(\gamma^2-4\alpha_1\eta) - 2d_1(\gamma\eta(16G\alpha_2 \\
&\quad - \beta_2^2) + 2\alpha_2\rho(2\beta_1\eta+\gamma\rho)) + c\Big(\alpha_2(\rho(-\beta_2(\gamma^2-8\alpha_1\eta) - 4\rho(\gamma^2+\alpha_1(-4\eta+\gamma(-1+\tau)))) \\
&\quad + 2\beta_1\eta(\beta_2\gamma - 4\alpha_1\rho(-1+\tau))) - 16G\alpha_2\gamma\eta(\gamma+2\alpha_1(-1+\tau)) + \beta_2^2\gamma\eta(\gamma+2\alpha_1(-1+\tau))\Big) \\
&\quad + 2(B+c_r)\alpha_1\gamma\eta\tau(16G\alpha_2-\beta_2^2) + 4\alpha_1\alpha_2\rho\tau(B+c_r)(2\beta_1\eta+\gamma\rho) + ((-16G\alpha_2+\beta_2^2)(\gamma^2-8\alpha_1\eta) \\
&\quad - 4\alpha_2\beta_1(2\beta_1\eta+\gamma\rho))\phi\Big]\Big[4X\Big]^{-1},
\end{aligned}$$

when $G > \frac{1}{16\alpha_2}[\beta_2^2 + \frac{\alpha_2(2\beta_1\eta+\gamma\rho)^2}{(4\alpha_1\eta-\gamma^2)\eta}]$,

$$X = [16G\alpha_2\eta(\gamma^2 - 4\alpha_1\eta) + \beta_2^2\eta(4\alpha_1\eta - \gamma^2) + \alpha_2(2\beta_1\eta + \gamma\rho)^2],$$

$$Y = [2c_r\beta_1\gamma\eta + 2A_1\gamma^2\rho + 3c_r\gamma^2\rho - 8A_1\alpha_1\eta\rho - 8c_r\alpha_1\eta\rho - 2d_1(2\beta_1\eta + \gamma\rho) + 2(B + c_r)\alpha_1(2\beta_1\eta + \gamma\rho)\tau],$$

$$Z = -\gamma(2\beta_1\eta + 3\gamma\rho) + \alpha_1(-4\beta_1\eta(-1 + \tau) + 2\rho(\gamma + 4\eta - \gamma\tau)),$$

$$U = \eta(2d_1 + 2c\alpha_1 + 2A_1\gamma - c\gamma + c_r\gamma) + 2\eta\tau\alpha_1(2A_2 - B - c + c_r) - \gamma\phi,$$

$$V = (8g\alpha_2 + d_2\beta_2)\eta(\gamma^2 - 4\alpha_1\eta) + \alpha_2\Big(\eta Y + c\eta(-\beta_2(\gamma^2 - 4\alpha_1\eta) + Z) + \gamma(2\beta_1\eta + \gamma\rho)\phi\Big).$$

3.2. Decision strategy II

In this strategy, each player determines his/her optimal decisions for each period individually. Under this dynamic contract [1,7,16], the manufacturer optimizes his profit for the first period and declares his wholesale price (w_1^{II}), and the product quality (q^{II}). Then the retailer sets his RVM (λ_1^{II}) and refund price (r^{II}) by optimizing profit for the first period. Next, at the beginning of the second period, the manufacturer declares his wholesale price (w_2^{II}) by optimizing his profit for the second period only and then the retailer sets his RVM (λ_2^{II}) by optimizing his profit for the second period. This decision strategy can be applied in the automobile industries, fashion design industries, online commerce (*e.g.*, Amazon.com, Snapdeal.com, Flipkart.com *etc.*), where the manufacturers upgrade their product features in a regular basis and change the prices accordingly. Under decision strategy II, the retailer first optimizes his profit for the first period and determines his RVM and refund price from the first order optimality condition. We denote this profit by $\varPi_{r1}(\lambda_1, r)$. The retailer's reaction (RVM and refund price) is obtained as

$$\lambda_1 = \frac{\big(2\eta(d_1 - w_1\alpha_1 + q\beta_1) - \gamma(\phi - q\rho - A_1\eta) + \gamma^2\tau(A_2 - B) - 2\alpha_1\eta\tau(A_2 - B)\big)}{w_1(4\alpha_1\eta - \gamma^2)},$$
$$r_1 = \frac{\big(\gamma(d_1 - w_1\alpha_1 + q\beta_1) - 2\alpha_1(\phi - q\rho - A_1\eta) + \alpha_1\gamma\tau(A_2 - B)\big)}{(4\alpha_1\eta - \gamma^2)}$$

The second order sufficient condition can be obtained from the Hessian matrix:

$$H_r^{II} = \begin{pmatrix} \dfrac{\partial^2\varPi_{r1}}{\partial\lambda_1^2} & \dfrac{\partial^2\varPi_{r1}}{\partial\lambda_1\partial r} \\ \dfrac{\partial^2\varPi_{r1}}{\partial r\partial\lambda_1} & \dfrac{\partial^2\varPi_{r1}}{\partial r^2} \end{pmatrix} = \begin{pmatrix} -2\alpha_1 w_1^2 & \gamma w_1 \\ \gamma w_1 & -2\eta \end{pmatrix}.$$

Here $|H_r^{II}| = (4\alpha_1\eta - \gamma^2)w_1^2 > 0$, if $\eta > \frac{\gamma^2}{4\alpha_1}$. The second order condition gives the uniqueness of the reaction. Next, the manufacturer optimizes his profit for the first period. We denote this profit by $\varPi_{m1}(w_1, q)$. The associated Hessian matrix is given by

$$H_m^{II} = \begin{pmatrix} \dfrac{\partial^2\varPi_{m1}}{\partial w_1^2} & \dfrac{\partial^2\varPi_{m1}}{\partial w_1\partial q} \\ \dfrac{\partial^2\varPi_{m1}}{\partial q\partial w_1} & \dfrac{\partial^2\varPi_{m1}}{\partial q^2} \end{pmatrix} = \begin{pmatrix} \dfrac{-4\alpha_1^2\eta}{(4\alpha_1\eta - \gamma^2)} & \dfrac{\alpha_1(2\beta_1\eta + \gamma\rho)}{(4\alpha_1\eta - \gamma^2)} \\ \dfrac{\alpha_1(2\beta_1\eta + \gamma\rho)}{(4\alpha_1\eta - \gamma^2)} & -2G \end{pmatrix}.$$

Therefore, $|H_m^{II}| = \frac{(4\alpha_1\eta-\gamma^2)8\alpha_1^2G\eta-\alpha_1^2(2\beta_1\eta+\gamma\rho)^2}{(4\alpha_1\eta-\gamma^2)^2}$.

This shows that H_m^{II} is negative definite and consequently, the reaction is unique provided that $\varPi_{m1}(w_1, q)$ satisfies the condition $G > \frac{(2\beta_1\eta+\gamma\rho)^2}{8\eta(4\alpha_1\eta-\gamma^2)}$. Using the first order conditions, we get the manufacturer's reaction for the first period as

$$q = -\frac{1}{(8G\eta(4\alpha_1\eta-\gamma^2)-(2\beta_1\eta+\gamma\rho)^2)}\Big[(2\eta(2c\alpha_1\beta_1\eta+2g(\gamma^2-4\alpha_1\eta)$$
$$+c\alpha_1\gamma\rho+A_1\gamma^2\rho-4A_1\alpha_1\eta\rho-d_1(2\beta_1\eta+\gamma\rho)+B\alpha_1(2\beta_1\eta+\gamma\rho)\tau)+\gamma(2\beta_1\eta+\gamma\rho)\phi)\Big],$$
$$w_1 = \frac{1}{4\alpha_1\eta}\Big[2d_1\eta+2c\alpha_1\eta+2A_1\gamma\eta+4A_2\alpha_1\eta\tau-2B\alpha_1\eta\tau-\gamma\phi$$
$$-\frac{1}{(8G\eta(+4\alpha_1\eta-\gamma^2)-(2\beta_1\eta+\gamma\rho)^2)}(2\beta_1\eta+\gamma\rho)\Big(2\eta(2c\alpha_1\beta_1\eta+2g(\gamma^2-4\alpha_1\eta)+c\alpha_1\gamma\rho$$
$$+A_1\gamma^2\rho-4A_1\alpha_1\eta\rho-d_1(2\beta_1\eta+\gamma\rho)+B\alpha_1(2\beta_1\eta+\gamma\rho)\tau)+\gamma(2\beta_1\eta+\gamma\rho)\phi\Big)\Big].$$

At the end of the first period, the retailer optimizes his profit portion during the second period and gives the unique reaction (as the second order derivative is $-2\alpha_2 w_2^2 < 0$) of RVM, which is given by

$$\lambda_2 = \frac{1}{2\alpha_2 w_2}\Bigg[d_2-\alpha_2 w_2+\beta_2\Bigg\{\frac{1}{(8G\eta(+4\alpha_1\eta-\gamma^2)-(2\beta_1\eta+\gamma\rho)^2)}\Bigg((2\eta(2c\alpha_1\beta_1\eta+2g(\gamma^2-4\alpha_1\eta)$$
$$+c\alpha_1\gamma\rho+A_1\gamma^2\rho-4A_1\alpha_1\eta\rho-d_1(2\beta_1\eta+\gamma\rho)+B\alpha_1(2\beta_1\eta+\gamma\rho)\tau)+\gamma(2\beta_1\eta+\gamma\rho)\phi)\Bigg)\Bigg\}\Bigg].$$

Then the manufacturer optimizes his profit portion during the second period and sets a unique optimal wholesale price w_2^{II}(as the second order derivative is $-\alpha_2 < 0$). Now, using the value of w_2^{II}, we can get the wholesale price, refund price and RVM in both the periods, which are given in the following proposition:

Proposition 3.2. *At the equilibrium, under decision strategy II, the manufacture's wholesale prices, product quality, the retailer's variable markups and refund price are given respectively by*

$$w_1^{II} = \frac{1}{4\alpha_1\eta}\Big[R-(2\beta_1\eta+\gamma\rho)\Big(2\eta c\alpha_1(2\beta_1\eta+\gamma\rho)+T\Big)S^{-1}\Big],$$
$$w_2^{II} = \frac{1}{2\alpha_2 S}\Big[d_2S-c(8G\alpha_2\eta(\gamma^2-4\alpha_1\eta)+(2\beta_1\eta+\gamma\rho)(2\alpha_2\beta_1\eta+2\alpha_1\beta_2\eta+\alpha_2\gamma\rho))-\beta_2T\Big],$$
$$q^{II} = -\Big(2\eta c\alpha_1(2\beta_1\eta+\gamma\rho)+T\Big)S^{-1},$$
$$\lambda_1^{II} = \Big[(\alpha_1((c\alpha_1-d1)8G\eta^2-4g\beta_1\eta^2-2g\gamma\eta\rho-2A_1\beta_1\eta^2\rho-A_1\gamma\eta\rho^2-8G\gamma^2\eta\tau(A_2-B)$$
$$+8G\alpha_1\eta^2\tau(4A_2-3B)-4\beta_1^2\eta^2\tau(A_2-B)-4\beta_1\gamma\eta\rho\tau(A_2-B)-(A_2-B)\gamma^2\rho^2\tau+4G\gamma\eta\phi))\Big]$$
$$\times\Big[(2g\beta_1\gamma^2\eta-8g\alpha_1\beta_1\eta^2-16A_1G\alpha_1\gamma\eta^2+2A_1\beta_1^2\gamma\eta^2+4G\eta(A_1\gamma+d_1)(\gamma^2-4\alpha_1\eta)$$
$$+\gamma(g\rho-2G\phi)(\gamma^2-4\alpha_1\eta)+3A_1\beta_1\gamma^2\eta\rho-4A_1\alpha_1\beta_1\eta^2\rho+A_1\gamma\rho^2(\gamma^2-2\alpha_1\eta)$$
$$+c\alpha_1(4G\eta(\gamma^2-4\alpha_1\eta)+(2\beta_1\eta+\gamma\rho)^2)+4G\alpha_1\gamma^2\eta\tau(2A_2-B)-16G\alpha_1^2\eta^2\tau(A_2-B)$$
$$+4A_2\alpha_1\beta_1\eta\tau(\beta_1\eta+\gamma\rho)+A_2\alpha_1\gamma^2\rho^2\tau)\Big]^{-1},$$
$$\lambda_2^{II} = \frac{1}{2}-c\alpha_2S\Big[(d_2S-c(8G\alpha_2\eta(\gamma^2-4\alpha_1\eta)+(2\beta_1\eta+\gamma\rho)(2\alpha_2\beta_1\eta+2\alpha_1\beta_2\eta+\alpha_2\gamma\rho))-\beta_2T\Big]^{-1}$$

TABLE 1. Optimal results under different strategies.

Optimal decisions	Decision strategy I	Decision strategy II
λ_1	0.625	0.572
λ_2	0.396	0.396
p_1	451.736	452.83
p_2	335.148	335.268
w_1	278.006	287.994
w_2	240.099	240.179
q	0.542	0.595
r	178.483	170.781
Π_m	14361.8	14327.
Π_r	9314.46	8749.03
Π	23676.3	23076

and

$$r^{II} = \Big[2g\beta_1\gamma\eta - 4A_1G\gamma^2\eta + 16A_1G\alpha_1\eta^2 - 2A_1\beta_1^2\eta^2 - g\rho(\gamma^2 - 8\alpha_1\eta) - A_1\beta_1\gamma\eta\rho - A_1\rho^2(\gamma^2 - 4\alpha_1\eta) + (d_1 - c\alpha_1)(4G\gamma\eta + \rho(2\beta_1\eta + \gamma\rho)) - 4BG\alpha_1\gamma\eta\tau - 2B\alpha_1\beta_1\eta\rho\tau - B\alpha_1\gamma\rho^2\tau + (2G(\gamma^2 - 8\alpha_1\eta) + \beta_1(2\beta_1\eta + \gamma\rho))\phi\Big]S^{-1}$$

when $G > \frac{(2\beta_1\eta+\gamma\rho)^2}{8\eta(4\alpha_1\eta-\gamma^2)}$,

$$S = (8G\eta(4\alpha_1\eta - \gamma^2) - (2\beta_1\eta + \gamma\rho)^2) > 0,$$

$$R = 2\eta(d_1 + c\alpha_1 + A_1\gamma + (2A_2 - B)\alpha_1\tau) - \gamma\phi,$$

$$T = 2\eta\Big(\big((2g + A_1\rho)(\gamma^2 - 4\alpha_1\eta) + (B\alpha_1\tau - d_1)(2\beta_1\eta + \gamma\rho)\big) + \gamma(2\beta_1\eta + \gamma\rho)\phi\Big).$$

4. Numerical analysis

In this section, a numerical example is taken to analyze the equilibrium results in two different strategies proposed. We consider the following data set: $d_1 = 150; d_2 = 120; \alpha_1 = 0.34; \alpha_2 = 0.28; \beta_1 = 0.82; \beta_2 = 0.84; \gamma = 0.35; \phi = 10; \eta = 0.2; \rho = 0.6; A_1 = 100; A_2 = 90; B = 75; c = 50; c_r = 15; g = 700; G = 800; H = 2000; \tau = 0.05$.

Table 1 shows that profits of both the players as well as the whole system and the refund price are higher in the decision strategy I than those in the decision strategy II. Further, the decision strategy II offers higher product quality than the decision strategy I. From the optimal results, it can be seen that although the wholesale price of the manufacturer and the selling price of the retailer are less in the decision strategy I, the retailer offers higher refund price, which is called "low price high refund" situation. On the other hand, we can see that the product quality and the refund price are complementary *i.e.* if the quality is high then the refund price would be low and vice-versa. During the second period, as the players entertain no return policy, they are interested in "high selling price, high quality" tactic. Also, we see that, although the refund price is higher in the decision strategy I, both the retailer and the manufacturer can achieve their best performances in terms of profit. In both the strategies, $p_1 > p_2$ and $w_1 > w_2$. The reason behind this result is that the retailer offers the return policy to the consumers in the first period only. The retailer compensates his cost due to the refund price paid by him to the consumers by increasing his selling price p_1, which forces the manufacturer to set higher w_1. Table 2 presents the optimal results when $\rho = 0$ *i.e.* when return quantity is independent of product quality. It is seen that the product quality is highly affected when quality is not taken into consideration in the product return. Table 3 indicates the optimal results when $\gamma = 0$ *i.e.* when the demand at the retailer in the first period

TABLE 2. Optimal results under different strategies when $\rho = 0$.

Optimal decisions	Decision strategy I	Decision strategy II
λ_1	0.624(−0.08%)	0.572(−0.11%)
λ_2	0.396(−0.01%)	0.396(−0.01%)
p_1	450.857(−0.19%)	451.784(−0.23%)
p_2	335.069(−0.02%)	335.103(−0.05%)
w_1	277.545(−0.17%)	287.446(−0.2%)
w_2	240.046(−0.02%)	240.069(−0.05%)
q	0.507(−6.43%)	0.522(−12.32%)
r	177.304(−0.66%)	169.452(−0.78%)
Π_m	14303.6(−0.41%)	14273(−0.38%)
Π_r	9310.04(−0.05%)	8741.92(−0.08%)
Π	23613.6(−0.27%)	23014.9(−0.27%)

The parentheses indicate % change w.r.t. the results given in Table 1.

TABLE 3. Optimal results under different strategies when $\gamma = 0$.

Optimal decisions	Decision strategy I	Decision strategy II
λ_1	0.391(−37.5%)	0.387(−32.3%)
λ_2	0.396(−0.01%)	0.396(−0.02%)
p_1	344.775(−23.68%)	345.235(−23.8%)
p_2	335.039(−0.03%)	335.067(−0.06%)
w_1	247.933(−10.82%)	248.823(−13.6%)
w_2	240.026(−0.03%)	240.045(−0.06%)
q	0.494(−8.92%)	0.506(−15.01%)
r	25.74(−85.57%)	25.759(−84.92%)
Π_m	9467.65(−34.08%)	9467.27(−33.92%)
Π_r	6863.8(−26.31%)	6835.27(−21.87%)
Π	16331.4(−31.02%)	16302.5(-29.35%)

The parentheses indicate % change w.r.t. the results given in Table 1.

is independent of the refund price. As there is no return policy in the second period, changes in RVM, p_2 and w_2 are negligible but the rest of the variables and profits are highly affected.

We can also see that the decision strategy I gives the best optimal result (except λ_1 and profits). The percentage changes in the optimal results with respect to Table 1 are shown in parentheses in both the cases. Table 4 indicates the optimal results when $w_1 = w_2 = w$ *i.e.* the manufacturer sets the same wholesale price for both the periods. We see that λ_1, p_1, q and r remain the same as given in Table 1. Also, w takes the value of w_1 in the decision strategy II; λ_2 is highly affected in both the strategies; p_2 and r in the decision strategy I increase but the profits of the manufacturer, the retailer and the whole system decrease in both the strategies.

TABLE 4. Optimal results under different strategies when $w_1 = w_2 = w$.

Optimal decisions	Decision strategy I	Decision strategy II
λ_1	0.693(+10.9%)	0.572(0%)
λ_2	0.308(−22.18%)	0.247(−37.57%)
p_1	450.665(−0.24%)	452.83(0%)
p_2	348.193(+3.89%)	359.176(+7.13%)
w	266.192(−4.25%)	287.994(0%)
q	0.541(−0.2%)	0.595(0%)
r	187.881(+5.26%)	170.781(0%)
Π_m	14223.3(−0.96%)	14006.9(−2.23%)
Π_r	9389.79(−0.81%)	7635.99(−12.72%)
Π	23613.1(−0.27%)	21642.9(−6.21%)

The parentheses indicate % change w.r.t. the results given in Table 1.

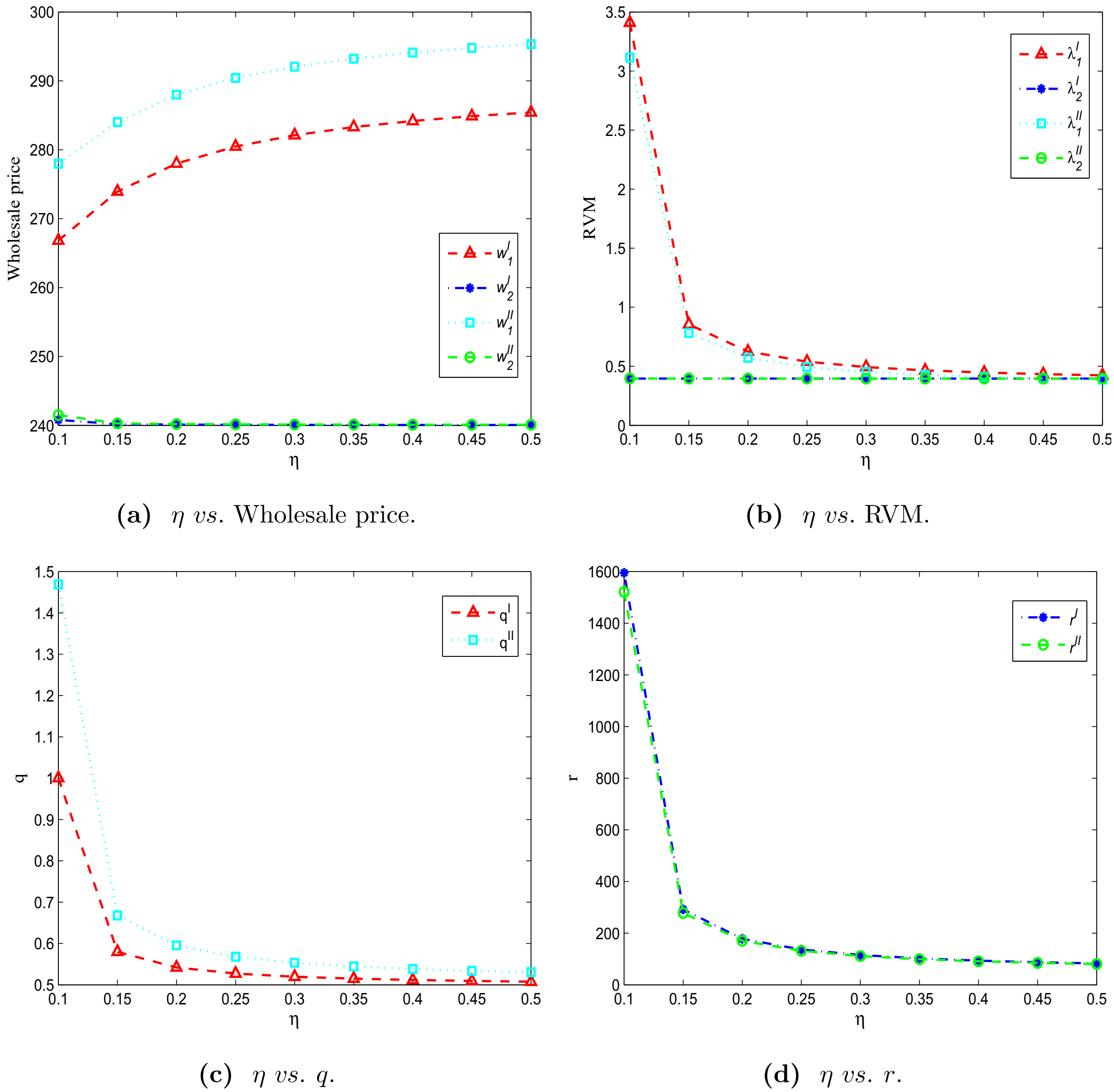
5. Sensitivity analysis

In this section, we discuss the sensitivity of some key parameters of the model for nonhomogeneous demand case. We keep the same values of the parameters as given in Example 1 but change the value of one parameter at a time to investigate its impact on the optimal solution. The sensitivity of the parameters η, γ, G and g is shown in Figures 2−5.

As the refund price sensitivity (η) on refund quantity increases, the wholesale price (w_1) of the first period increases but the wholesale price (w_2) of the second period remains unchanged in both the strategies (Fig. 2a). RVM (λ_1) of the first period decreases but that in the second period is not affected with the change of η in both the strategies (Fig. 2b). As the sensitivity of the refund price increases, the manufacturer need not to offer higher refund price to attract customers. So s/he decreases the refund price and consequently decreases the product quality which affects the market demand (Figs. 2c, 2d). It has more negative impact on the retailer's profit than the manufacturer's profit in both the decision strategies. Due to decrease in the refund price, it is obvious from the demand function that the demand rate in the first period decreases but it, in the second period, remains unchanged as being independent of refund price in both the strategies. Immediate return rate first increases and then decreases while the used product return rate remains the same in both the strategies.

When the refund price sensitivity (γ) on the first period's demand increases, it has positive impact on the first period's wholesale price and RVM increases rapidly whereas it has almost no impact on the second period's wholesale price and RVM in both the strategies (Figs. 3a, 3b). As γ increases, the refund price and the product quality increase in both the strategies (Figs. 3c, 3d). The profits of both the retailer and the manufacturer increase as the demand rate increases. It is quite obvious that when γ increases, the first period's demand rate increases whereas the second period's demand rate remains unchanged. As the refund price increases, the customers have the tendency to return. So the immediate return rate increases but there is no effect on the used product return rate in both the strategies.

As quality maintenance cost parameter G increases, the wholesale price and RVM decrease in both the decision strategies (Figs. 4a, 4b). The quality maintenance cost increases means the manufacturer has to invest more to keep the quality of the product same. As a result, the product quality and the refund price decrease significantly for higher maintenance cost (Figs. 4c, 4d). The manufacturer's profit decreases more significantly than that of the retailer as G increases in both the strategies. The demand rate decreases as the product quality decreases. The return rate remains the same for both the periods and in both the strategies.



(a) η *vs.* Wholesale price. **(b)** η *vs.* RVM.

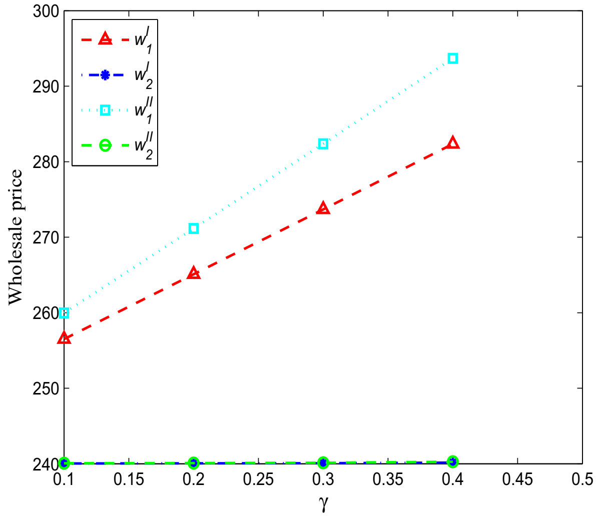
(c) η *vs.* q. **(d)** η *vs.* r.

FIGURE 2. Change (%) in optimal results w.r.t. η.

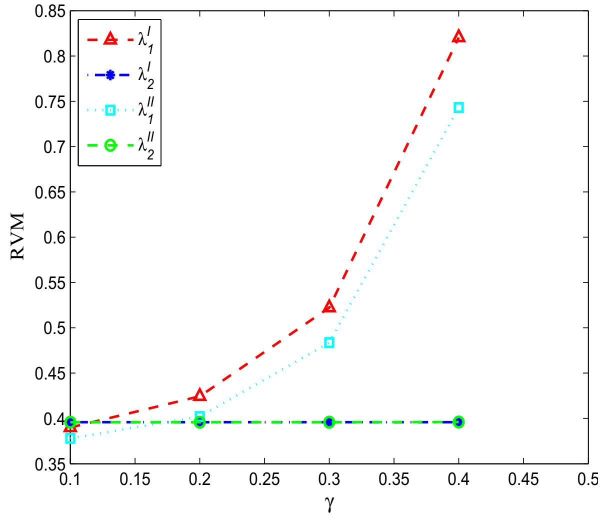
The goodwill lost cost (g) only affects the manufacturer's profit, product quality and refund price. When the goodwill lost cost increases, the manufacturer increases his/her product quality and refund price. In doing so, he losses his/her profits marginally in both the decision strategies (Fig. 5).

6. Conclusions and future research directions

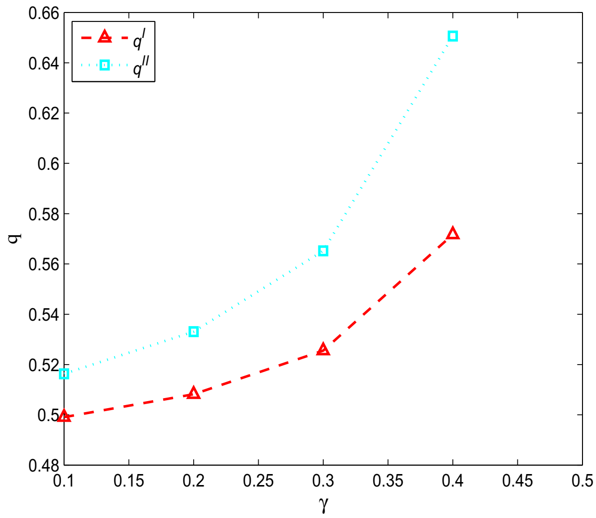
In this paper, we consider a two-period CLSC model with a single manufacturer and a single retailer where the manufacturer is considered as the Stackelberg leader and the retailer as the follower. We analyze the impacts of selling price, product quality and return policy on the market demand and profits of the manufacturer, the



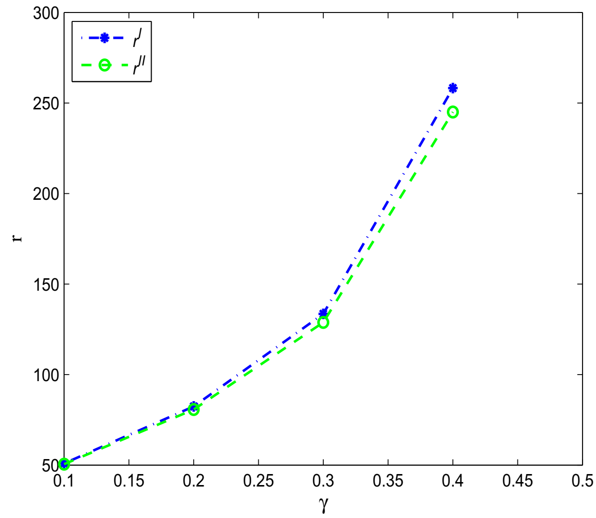
(a) γ *vs.* Wholesale price..



(b) γ *vs.* RVM.



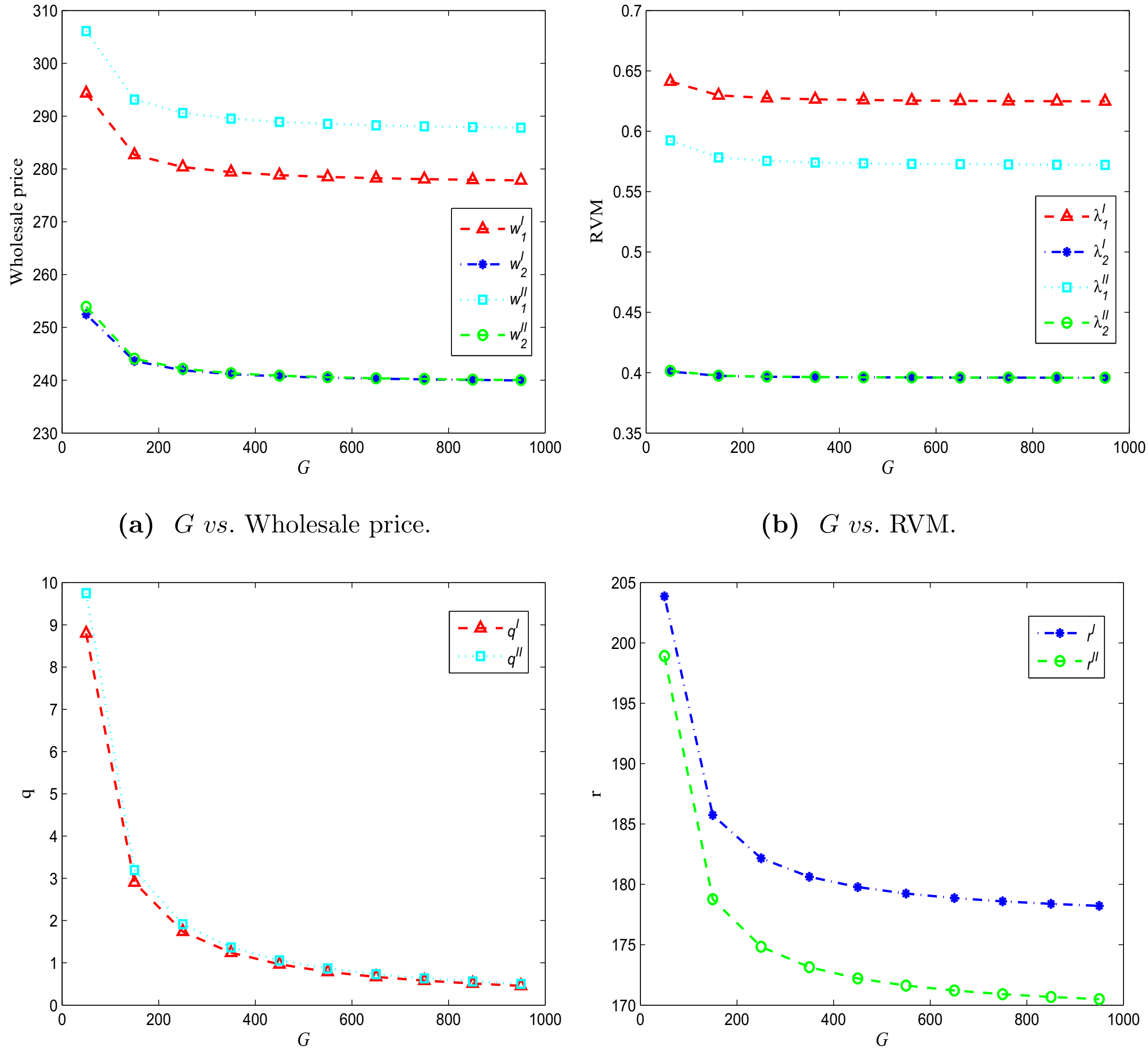
(c) γ *vs.* q.



(d) γ *vs.* r.

FIGURE 3. Change (%) in optimal results w.r.t. γ.

retailer and the whole system. We assume the selling prices as the variable markups on the wholesale prices. The market demand during the first period is dependent on the selling price, product quality and the refund price while in the second period, it is independent of the refund price. The retailer considers two types of return viz. immediate return and used product return. We construct the profit functions of the manufacturer and the retailer under two different decision strategies. In the decision strategy I, the manufacturer and the retailer optimize their total profits and decide the optimal decisions whereas, in the decision strategy II, they optimize their profits individually for both the periods and decide the optimal decisions.



(a) G *vs.* Wholesale price.

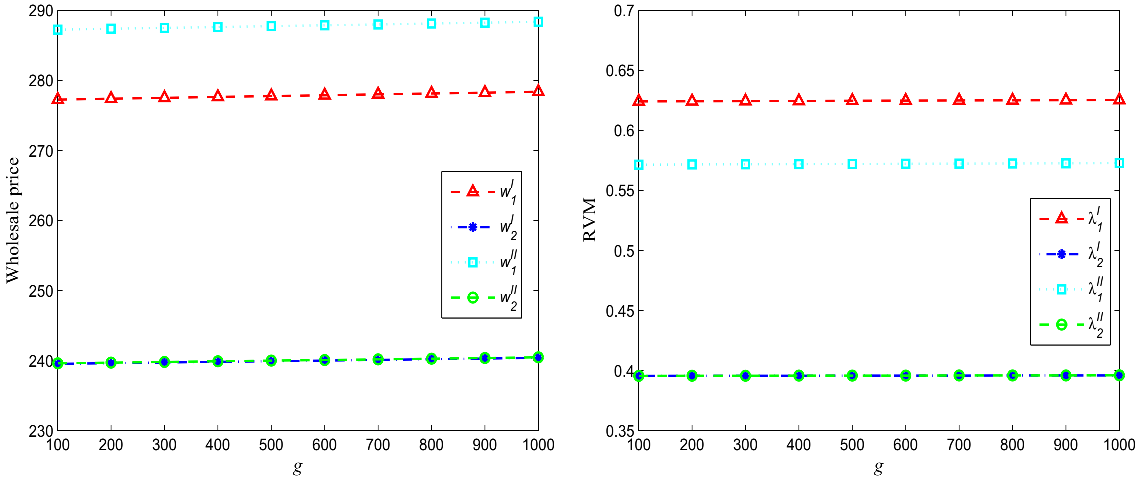
(b) G *vs.* RVM.

(c) G *vs.* q.

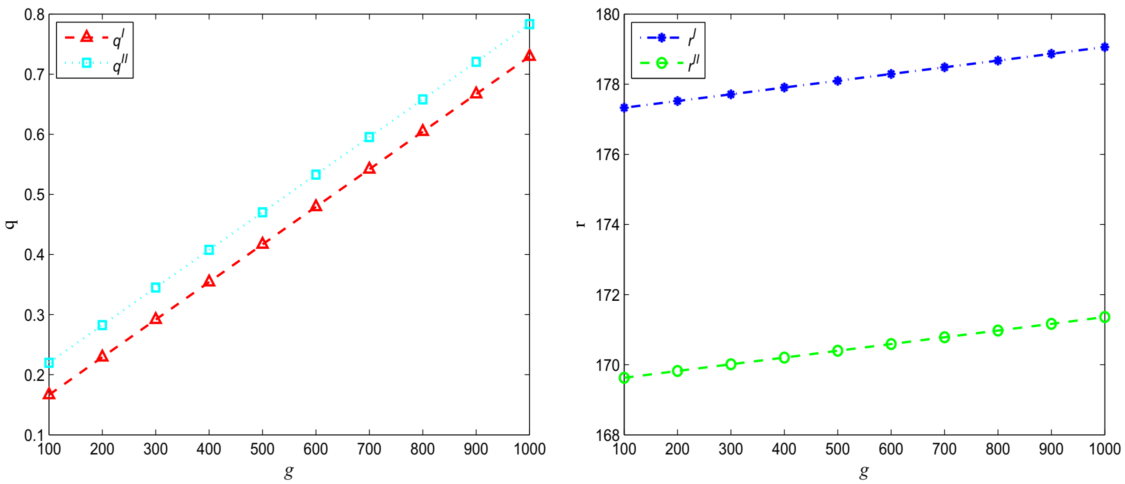
(d) G *vs.* r.

FIGURE 4. Change (%) in optimal results w.r.t. G.

From the numerical study, we conclude that the decision strategy I gives better result in terms of profit and refund price, whereas the decision strategy II offers better product quality. We also see that although the selling price is higher in the first period, consumers are keen to buy more products because of the return policy and the freshness of the product. Comparing the two decision strategies period-wise, we conclude that when the product quality is better, the manufacturer and the retailer should charge higher wholesale and selling prices, respectively (under strategy II), but for lower product quality, the retailer offers a higher refund price (under strategy I). When the return rate is independent of the product quality, all the optimal decisions change insignificantly except the product quality which is highly affected in both the decisions strategies. When the demand rate in the first period is independent of the refund price, all the optimal decisions including the profit



(a) g *vs.* Wholesale price. **(b)** g *vs.* RVM.



(c) g *vs.* q. **(d)** g *vs.* r.

FIGURE 5. Change (%) in optimal results w.r.t. g.

of the manufacturer, the retailer and the whole system are highly affected whereas those are affected very less in the second period. When the manufacturer sets the same wholesale price for both the periods, the retailer charges higher selling price in the second period (in both the strategies) and offers higher refund price (in strategy I). In this case, the profits of the manufacturer, the retailer and the whole system decrease sharply.

Similar to any other model, our model is based on a set of assumptions. For example, the demand is assumed to be deterministic. So one can consider stochastic demand instead of deterministic demand. We have considered a two-period model in which the return is limited to the first period only. One can extend the model to a multi-period scenario and apply the return policy to all the periods. We have analyzed the model considering manufacturer-Stackelberg gaming approach. Consideration of other Stackelberg games could be taken as future research efforts. One may also include a third party as collection option for the closed-loop supply chain.

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