Journal of Cleaner Production 140 (2017) 1514–1527

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# Optimal retailer investments in green operations and preservation technology for deteriorating items

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ARTICLE INFO

*Article history:*
Received 21 April 2016
Received in revised form
3 September 2016
Accepted 30 September 2016
Available online 3 October 2016

*Keywords:*
Green retailing
Preservation technology investment
Reference price
Optimal control
Simulated annealing algorithm

ABSTRACT

This paper examines the impact of dynamic retailer investments in green operations while considering the reference price effect. A replenishment problem based on joint pricing, dynamic investment in green operations, preservation technology, and optimal replenishment times for deteriorating items is considered as a way to maximize retailer profit. In this problem, the demand rate depends on the sales and reference prices as well as green concern level. Optimal control theory is employed to obtain a dynamic investment rate, and a simulated annealing algorithm is used to find the solution of the nonlinear constraint optimization problem, which determines the price, preservation technology investment, and replenishment cycle time. In addition, computational simulations and sensitivity analyses are carried out to offer managerial insights. The findings suggest that continuous investment in green operations and preservation technology can significantly improve the retailer's financial performance. The consumer reference price is an important influence on the retailer's decision to invest in green operations. Furthermore, results show that the higher price sensitivity of the market always discourages the retailer from investing in green operations. The retailer needs to invest more in green operations for products with relatively high unit value.

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## 1. Introduction

Global retailers' environmentally sustainable, socially responsible, and economically profitable business practices demonstrate that green retailing (GR) is no longer an optional opportunity but an essential part of the business model. GR has become popular among retailers striving to balance economic gains with environmental performance in the face of growing pressures from customers, regulators, non-governmental organizations, and other stakeholders. Among different eco-friendly activities, most retailers willingly attempt to follow GR to save energy, contribute to an eco-efficient environment, use natural resources for sustainability, retain and motivate employees, reduce waste generated from stores, and remodel store settings and designs (Lai et al., 2010; Jones et al., 2011; Chkanikova and Lehner, 2015; Tang et al., 2016). Retailers such as Tesco, Carrefour, Wal-Mart, and Zara have adopted environmental protection measures for managing and enlightening their retail operations. For example, the UK retailer Tesco emphasizes reduced carbon emissions and promises to be a zero-carbon business by 2050. The Spanish retailer Zara introduced a waste management policy for its flagship stores by using organic cotton and ecological fabrics as well as by educating its staff on ways to limit energy consumption. The retail giant Wal-Mart introduced green store operations to help conserve energy and promote waste recycling. One of Japan's largest retail chains, AEON, introduced green store operations called “my basket” to enhance customer service and to reduce the use of plastic shopping bags (AEON, 2010). One of the more than 300 grocery store chains in the United States, Whole Foods Market sells natural foods to create a green reputation and protect the environment from harmful chemicals (www.wholefoodsmarket.com). Patagonia, which primarily sells tools for climbers, also offers clothes of recycled polyester, rather than pesticide-intensive cotton, to promote environmentally conscious marketing (www.patagonia.com). BestBuy, a popular retailer of home appliances and consumer electronics, won ENERGYSTAR honors in both 2008 and 2009 for promoting green products (www.bestbuy.com).

Researchers and practitioners have also investigated different

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http://dx.doi.org/10.1016/j.jclepro.2016.09.229
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aspects of GR from various perspectives (De Brito et al., 2008; Xie, 2015; Richman and Simpson, 2016). In a recent empirical study on Korean consumers, Ko et al. (2013) found that consumers' perceptions of retailers using green marketing programs influence their intentions to purchase products from the seller. Through a survey on a large retailer operating in the United Kingdom, Morgan et al. (2015) also found that the GR policy affects consumer choice and argued that retailers have many opportunities to improve their communications on the coherence and planning of initiatives designed to help their customers reduce emissions. Bradley (2016) proposed an outline for measuring emissions and water used in food retail businesses. Li et al. (2016a, b) analyzed the pricing strategy of a dual-channel supply chain by considering the effects of green policies on customer choices. They concluded that the decision to open a direct channel is largely influenced by the greening cost; that is, ability to increase product compatibility with the environment without compromising its qualitydrives the investment decision. Jakobsen and Clausen (2016) argued that environmental innovation should be integrated in products and processes to achieve environmental goals. However, there is a long-standing debate about whether "it pays to be green" (Ambec and Lanoie, 2008; Ghisetti and Rennings, 2014). Some empirical studies (European Social Investment Forum, 2012; Nyilasy et al., 2014) reported that the retailer perceives that GR investments have a positive impact on society and the environment and that their investments demonstrate their position as powerful and trustworthy actors for the welfare of the environment. In a recent survey by Li et al. (2016a, b), it is argued that the green sustainability program can significantly improve the financial performance of fashion enterprises, and it helps them mitigate the critical consequence of a financial tsunami. However, in some empirical studies, the effect of environmental sustainability was shown to have an insignificant effect on economic performance (Peattie and Crane, 2005; Henri and Journeault, 2010).

In this study, an analytical assessment is made to find answers to the research question: Does the investment in GR operations financially benefit retailers? Although in the literature, authors have defined "green" in different ways (Ahi and Searcy, 2013; Fichtinger et al., 2015), green operations typically include investments in employee compensation, donations, local sourcing, recyclable materials and energy conservation, emissions and waste, labor relations, occupational health and safety, equal labor, and store settings and design. According to previous studies of many retailers, the impact of consistent green operations on market demand is referred as the "*green concern level*" (GCL). The objective of this study is to identify the important factors influencing the profitability of a retailer who simultaneously invests in green operations and preservation technology by considering the dynamics of investment and the reference price effect.

The deterioration of most physical goods is a natural process that cannot be stopped; however, it can be slowed down with preservation technology. Investment in preservation technology is important to sustainable product lifecycle management. A recent empirical study on deteriorating items suggests that the total profit of a store may increase by 33% if it can reduce 20% of its perishable waste (The Profit Experts, 2011). These findings have motivated several researchers and marketers to study the effect of preservation technology investment in reducing item deterioration. Hsu et al. (2010) first investigated the impact of preservation technology investment on an exponentially decaying inventory model involving partial backorders. On the basis of Hsu et al. (2010), Lee and Dye (2012) established an inventory model with a stock-dependent selling rate and a preservation technology investment in which the shortages are allowed and partially backlogged. The authors concluded that if the deterioration rate is high, then more investment is needed. Dye (2013) has explored the effect of preservation technology investment on a non-instantaneously deteriorating item. Tsao (2016) extended the model of Dye (2013) to consider a joint location and preservation technology investment decision-making problem for non-instantaneous deteriorating items while taking trade credit into account. Yang et al. (2015) investigated the trade-off between preservation technology investment and the optimal dynamic trade credit for a deteriorating inventory model. Zhang et al. (2014a, b) and Liu et al. (2015) explored the characteristics of preservation technology investment for deteriorating items. However, the effect of reference price was ignored in these studies.

Customer purchasing decisions are influenced by reference price (Greenleaf, 1995), and the effects of reference price can be found in the experimental and analytical modeling literature. When they consider buying an item, consumers compare the reference price, which they determine mentally, to the shelf price of products (Fibich et al., 2003; Taudes and Rudloff, 2012). A strong effect of reference price on purchasing decisions was found in experimental research conducted by Mazumdar et al. (2005). Kopalle and Winer (1996) presented an optimal control model that incorporates the relationship between the reference price and the product quality expected by consumers, and they analytically derived optimal dynamic pricing and product quality policies. Fibich et al. (2003) analyzed the reference price effects on the optimal pricing strategies under open-loop and closed-loop equilibria. Popescu and Wu (2007) extended the results of Fibich et al. (2003) and applied them to a general form of the demand function, and they argued that managers who ignore long-standing reference price may lose substantial revenue. Geng et al. (2010) suggested that in a single-manufacturer single-retailer supply chain, the retailer prefers a periodic promotion strategy over a constant price strategy in the presence of asymmetric reference price effects. Nasiry and Propescu (2011) presented a dynamic pricing model under a reference price effect with weighted averages of the lowest and most recent prices. Güler (2013) showed the impact of the reference price effect under a periodic review inventory system. Xue et al. (2016) studied a dynamic pricing model for deteriorating items while considering the reference price effect. Zhang et al. (2014a, b) investigated reference price effects in a two-period pricing model. The reference price effect in a supply chain environment was also presented in recent studies by Martín-Herrán and Taboubi (2015) and Lin (2016). The authors concluded that the optimal profit of the channel is considerably influenced by the customer reference price.

A pricing and replenishment strategy for a deteriorating inventory system is a fundamental area of research, which is used to explore the in-depth impacts of investments in green operations and preservation technology on the profitability of a retailer. Specifically, a determination is sought for a retailer selling deteriorating items while simultaneously considering the impact of reference price and preservation technology investment. Therefore, the following research issues are merged in this study: investment in green operations, preservation technology investment in deteriorating items, a pricing and replenishment schedule, and the reference price effect. The study adds to the existing literature in three important ways. First, the model developed in this study is a nonlinear constraint optimization problem. It is difficult to find the optimum solution via an analytical approach due to its complexity. Therefore, the analytical form of the optimal investment rate is determined through use of Pontryagin's maximum principle, and a simulated annealing (SA) algorithm is used to obtain the optimal joint pricing, investment amount, order quantity, and replenishment cycle time. Until now, no analytical study has been undertaken to address the problem of dynamic investment in green

operations. Second, the findings show that continuous investment in green operations is always profitable for the retailer. The consumers' initial reference price and the unit price of the product are important factors influencing a retailer's decision to invest in green operations. Finally, this study provides important implications for both academia and industry. The analytical study associates the influencing effect of dynamic investment on green operations with the replenishment decision of a retailer, which contributes to academic sustainability research. In addition, the study informs many in industry, such as the retailer who receives affirmation about the financial benefit of voluntarily under taking green operations.

## 2. Model formulation

The following notations are adopted throughout this paper:

### 2.1. Model development

The model considers a pricing and replenishment decisions of a retailer who sells a single item. The market demand rate $D(p,G(t),r(t))$ is a function of the sales price ($p$), GCL ($G(t)$), and reference price ($r(t)$). The functional form of market demand is as follows:

$$D(p,G(t),r(t)) = \alpha - \beta p + \gamma G(t) - \eta(p - r(t)) \quad (1)$$

where $\alpha > 0$ is the basic market potential, $\beta > 0$ represents the sensitivity of the demand rate with respect to price, $\gamma > 0$ reflects the sensitivity of the GCL, and $\eta > 0$ reflects the effect of the reference price. Thus, when $p \geq r(t)$, the demand decreases with respect to $p - r(t)$ and if $p < r(t)$, the demand increases with respect to $p - r(t)$. The investment in green operations not only enriches the retailer's image as an environmentally friendly representative but it also creates awareness among customers. Moreover, consumers incorporate green factors into their buying decisions. Therefore, the impact of GCL cannot be ignored by a retailer who would like to determine tangible optimal replenishment and investment levels. Although one can consider the impact of dynamic sales price in this model, frequent changes in the sales price may affect branding such that a retailer's goodwill is questioned. As a result, fluctuating prices may negatively influence consumer purchasing decisions and thus may prove a problematic strategy for increasing retailer profit. Moreover, dynamic price changes sometime enhance operational difficulties. Thus, the sales price $p$ is treated as a static variable. The differential equation representing the instantaneous inventory level $I(t)$ is given by

$$\dot{I}(t) = -D(p,G(t),r(t)) - \theta I(t), \;\; I(T) = 0 \quad (2)$$

where $\theta \equiv \theta(u) = \theta_0 e^{-\xi u}$ represents the positive deterioration rate coefficient of the product which is affected by the investment $u$ in preservation technology, where $\theta_0$ represents the deterioration under natural condition. The deterioration of inventory is proportional to the inventory level, and takes the deterioration rate as $\theta I(t)$. Additionally, due to the deteriorating nature of the item, the inventory level at the end of the replenishment cycle is set to zero, i.e. $I(T) = 0$ and shortages are not allowed. The retailer usually adjusts investment in green operations through the replenishment cycle. Therefore, the following differential equation that describes the time evolution of the GCL:

$$\dot{G}(t) = g(t) - \rho G(t) - \theta \tau I(t), \;\; G(0) = G_0 \quad (3)$$

The GCL ($G(t)$) increases with respect to investment in green operations and $\rho$ represents the decay rate of the GCL and its initial value $G_0 \geq 0$. Note that if the retailer invests in the previous cycle, then $G_0 > 0$. $\tau > 0$ represents the decay rate of the GCL with respect to the product deterioration rate $\theta$. If the deterioration rate increases, then the retailer has to invest more in disposing of or recycling the product. The investment in green operations of the retailer is assumed as $\frac{1}{2}k_1 g^2(t)$, where $k_1 > 0$ represents an increasing marginal cost of investment which is commonly applied in the existing literature (Saha, 2013; Xie, 2015).

The reference price is viewed as a predictive price expectation. The dynamics of reference price can be described (Kopalle and Winer, 1996) by the following differential equation

$$\dot{r}(t) = \delta(p - r(t)), \;\; r(0) = r_0 \quad (4)$$

where $r_0 > 0$ is the initial reference price and $\delta > 0$ is interpreted as the “memory parameter”, that reflects the memory impact on the reference price. If the reference price is low, then the retailer has fewer opportunities to invest both in preservation technology and green operations. High price sensitivity is a barrier to retailer investments in green operations. Therefore, to make the best investment decision, the retailer considers the effect of reference price. It is assumed that the inventory holding cost is a linear function of the current inventory level. The objective is to find a joint pricing, replenishment, dynamic investment in green operations and preservation technology investment policy for the retailer while maximizing the total profit per unit time, which can be formulated as

| | |
|---|---|
| $I(t)$ | inventory level at any time $t \in [0,T]$; |
| $I_0$ | initial inventory level, where $I_0 > 0$; |
| $T$ | length of replenishment cycle; |
| $A$ | sreplenishment cost per order; |
| $c$ | purchasing cost per unit; |
| $h$ | unit inventory holding cost per unit time; |
| $p$ | sales price per unit, where $p \geq c$; |
| $g(t)$ | dynamic investment rate in green operations at any time $t \in [0,T]$; |
| $G(t)$ | green concern level at any time $t \in [0,T]$; |
| $r(t)$ | reference price at time t; |
| $u$ | preservation technology investment to reduce deterioration rate, $u \geq 0$; |
| $\theta(u)$ | deterioration rate coefficient under preservation technology investment $u$; |
| $k_1$ | increased marginal cost for investment at any time $t \in [0,T]$; |
| $r$ | a random number, where $r \in (0,1)$; |
| $\beta$ | price-elasticity of product at any time $t \in [0,T]$; |
| $\gamma$ | sensitivity of GCL in demand of the product at any time $t \in [0,T]$; |
| $\xi$ | preservation technology investment efficiency coefficient; |
| $\Pi$ | total profit per unit time. |

$$\text{Maximize } \Pi = \frac{1}{T}\Big[\text{Sales revenue} - \text{Holding cost} - \text{Green operations cost} - \text{Purchase cost} - \text{Replenishment cost per order} - \text{Preservation technology investment cost}\Big] \tag{5}$$

$$\text{Maximize } \Pi = \frac{1}{T}\int_0^T \left[pD(p,G(t),r(t)) - hI(t) - \frac{1}{2}k_1 g^2(t)\right] dt - \frac{cI_0 + A + u}{T}$$

$$\begin{aligned}\text{subject to } \quad & \dot{I}(t) = -D(p,G(t),r(t)) - \theta I(t)\\ & \dot{G}(t) = g(t) - \rho G(t) - \theta\tau I(t)\\ & \dot{r}(t) = \delta(p - r(t))\\ & I(T) = 0, G(0) = G_0, r(0) = r_0, u \geq 0,\\ & g(t) \geq 0, \theta = \theta_0 e^{-\xi u}, \text{and } p \geq c.\end{aligned}$$

Note that the initial replenishment quantity $I_0$ is a decision variable in the above optimization problem, although for analytical tractability several authors assumed that purchase cost is zero under a dynamic environment (Kumar and Sethi, 2009; Xue et al., 2016). This paper considers $I_0$ as a dependent-decision variable. Once the decision variables $p$, $u$, $g(t)$, $r(t)$, $G(t)$, and $T$ are obtained, the replenishment quantity $I_0$ can be determined. Now for given $u$, $p$, and $T$, the following optimal control problem is solved by considering the reduced objective function ($J$) as defined below:

$$\text{Maximize } J = \frac{1}{T}\int_0^T \left[p(\gamma G(t) + \eta r(t)) - hI(t) - \frac{1}{2}k_1 g^2(t)\right] dt \tag{6}$$

$$\begin{aligned}\text{subject to } \quad & \dot{I}(t) = -D(p,G(t),r(t)) - \theta I(t)\\ & \dot{G}(t) = g(t) - \rho G(t) - \theta\tau I(t)\\ & \dot{r}(t) = \delta(p - r(t))\\ & I(T) = 0, G(0) = G_0, r(0) = r_0, \text{and } g(t) \geq 0.\end{aligned}$$

In the next section, the solution procedure to find the optimal replenishment strategy is discussed.

## 3. Solution procedure

In this section, Pontryagin's maximum principle is used to seek for the optimal dynamic variables for the given replenishment cycle, preservation technology investment and price of the product. Then, a simulated annealing algorithm is used to find values of the decision variables. Applying the concept of optimal control theory (Sethi and Thompson, 2000), the adjoint variables $\lambda_1$, $\lambda_2$, and $\lambda_3$ associated with the state variables $I$, $G$, and $r$ respectively are introduced, and the Hamiltonian is formulated as follows:

$$\begin{aligned}H(g,I,G,\lambda_1,\lambda_2,\lambda_3,t) &= p[\gamma G(t) + \eta r(t)] - hI(t) - \frac{1}{2}k_1 g(t)^2\\ &+\lambda_1[-\alpha + \beta p - \gamma G(t) + \eta(p - r(t)) - \theta I(t)] + \lambda_2[g(t) - \rho G(t) - \theta\tau I(t)] + \lambda_3\delta[p - r(t)]\end{aligned} \tag{7}$$

Note that the initial condition $I(0)$ and the terminal conditions $G(T)$ and $r(T)$ remain free, which introduce the following transversality conditions as $\lambda_1(0) = 0$, $\lambda_2(T) = 0$, and $\lambda_3(T) = 0$. Moreover, the adjoint variables $\lambda_1$,$\lambda_2$, and $\lambda_3$ must satisfy the following adjoint equations as:

$$\dot{\lambda_1} = -\frac{\partial H}{\partial I} = h + \theta\lambda_1 + \theta\tau\lambda_2 \tag{8}$$

$$\dot{\lambda_2} = -\frac{\partial H}{\partial G} = \lambda_1\gamma + \rho\lambda_2 - \gamma p \tag{9}$$

$$\dot{\lambda_3} = -\frac{\partial H}{\partial r} = \delta\lambda_3 - p\eta + \eta\lambda_1 \tag{10}$$

Equations (8)–(10) represent the system of simultaneous linear differential equations. To find the solution, an elimination technique is used, and the following notations are introduced as a matter of convenience, namely,

$$m_1 = \frac{1}{2}\left[\theta + \rho + \sqrt{(\rho - \theta)^2 + 4\theta\tau\gamma}\right]$$

$$m_2 = \frac{1}{2}\left[\theta + \rho - \sqrt{(\rho - \theta)^2 + 4\theta\tau\gamma}\right]$$

$$\Delta_1 = (m_1 - \rho)e^{m_1 T} - (m_2 - \rho)e^{m_2 T}$$

$$c_1 = \frac{\gamma\left[(p\gamma\theta\tau + h\rho)e^{m_2 t} + (m_2 - \rho)(p\theta + h)\right]}{\Delta_1\theta(\rho - \gamma\tau)}$$

$$c_2 = \frac{-\gamma\left[(p\gamma\theta\tau + h\rho)e^{m_1 t} + (m_1 - \rho)(p\theta + h)\right]}{\Delta_1\theta(\rho - \gamma\tau)}$$

Eliminating $\lambda_1(t)$ from Equations (8) and (9), one yields

$$\Big[D^2 - (\theta + \rho)D + \theta(\rho - \tau\gamma)\Big]\lambda_2(t) = \gamma(p\theta + h) \tag{11}$$

where $D \equiv \frac{d}{dt}$. The solution of Equation (11) is the sum of a complementary function and a particular integral, where $m_1$ and $m_2$ represent characteristics root of Equation (11). By solving Equation (11) and substituting the value of $\lambda_2(t)$ in Equation (8), one may obtain $\lambda_1(t)$. On simplification and using transversality conditions, the adjoint variables are obtained as follows:

$$\lambda_1(t) = \frac{m_1-\rho}{\gamma}c_1e^{m_1t} + \frac{m_2-\rho}{\gamma}c_2e^{m_2t} - \frac{p\gamma\theta\tau + h\rho}{\theta(\rho-\tau\gamma)} \tag{12}$$

$$\lambda_2(t) = c_1e^{m_1t} + c_2e^{m_2t} + \frac{p\gamma\theta + h\gamma}{\theta(\rho-\tau\gamma)} \tag{13}$$

where all the parameters are defined above. By using Equations (12) and (13) in Equation (10) with the transversality condition $\lambda_3(T) = 0$, one can obtain the value of the adjoint variable $\lambda_3(t)$ as given below:

$$\begin{aligned}\lambda_3(t) =& \frac{\eta p}{\delta}\left(1-e^{-\delta(T-t)}\right) + \frac{c_1\eta(m_1-\rho)e^{m_1t}}{\gamma(m_1-\delta)}\left(1-e^{(m_1-\delta)(T-t)}\right)\\ &+ \frac{c_2\eta(m_2-\rho)e^{m_2t}}{\gamma(m_2-\delta)}\left(1-e^{(m_2-\delta)(T-t)}\right)\\ &+ \frac{\eta(p\gamma\theta\tau+h\rho)}{\theta\delta(\rho-\tau\gamma)}\left(1-e^{-\delta(T-t)}\right)\end{aligned} \tag{14}$$

In the above analysis, it is assumed that $m_1 \neq m_2 \neq \delta$ and $\rho \neq \tau\gamma$ for the generalization. If equality occurs, one needs to consider a limited case to obtain solutions.

**Proposition 1**. For a given price p, the preservation technology investment u, and the length of replenishment cycle T, the retailer is able to invest in green operations if $p \geq \Gamma$ and the optimal investment rate is governed by the following equation:

$$g(t) = \frac{1}{k_1}\left[c_1e^{m_1t} + c_2e^{m_2t} + \frac{p\gamma\theta+h\gamma}{\theta(\rho-\tau\gamma)}\right] \tag{15}$$

$$\text{where}\,\Gamma = \frac{h\left[m_1\left(1-e^{m_2T}\right) - m_2\left(1-e^{m_1T}\right)\right]}{\theta\left[(\rho-\gamma\tau)\left(e^{m_1T}-e^{m_2T}\right) - \left(m_1\left(1-e^{m_2T}\right) - m_2\left(1-e^{m_1T}\right)\right)\right]}$$

**Proof:** The optimal control policy for the investment in green operations $g^*$ should maximize the Hamiltonian function for every value, i.e.,

$$H(I,G,g^*,u,r,\lambda_1,\lambda_2,\lambda_3,t) \geq H(I,G,g,u,r,\lambda_1,\lambda_2,\lambda_3,t)$$

From Equation (7), it is observed that the Hamiltonian H is a strictly concave function of g. By maximizing H, one can obtain the investment rate in green operations as follows

$$g(t) = \frac{\lambda_2(t)}{k_1}$$

The substitution of $\lambda_2(t)$ yields the result given in Equation (15). Moreover, the retailer will invest in green operations if

$$\begin{aligned}g(0) = \frac{1}{\Delta_1}\Bigg[&p\left(e^{m_1T}-e^{m_2T}\right) - \frac{(p\theta+h)}{\theta(\rho-\gamma\tau)}\left(m_1\left(1-e^{m_2T}\right)\right.\\ &\left.- m_2\left(1-e^{m_1T}\right)\right)\Bigg] \geq 0\end{aligned}$$

After rearrangement one may obtain above limit of the selling price p. The proof is complete.

From Proposition 1, one can conclude that there exists a threshold for the sales price, below which the investment in green operation is not profitable for the retailer. Because $\lambda_2(T) = 0$, the investment rate must be decreasing throughout the replenishment cycle. By solving Equation (4) with the boundary condition, the reference price is obtained as follows:

$$r(t) = p\left(1-e^{-\delta t}\right) + r_0e^{-\delta t} \tag{16}$$

As a matter of convenience, to determine $G(t)$ and $I(t)$, the following notations are introduced, namely,

$$n_1 = \frac{1}{2}\left[\sqrt{(\rho-\theta)^2+4\theta\tau\gamma} - (\theta+\rho)\right]$$

$$n_2 = -\frac{1}{2}\left[\sqrt{(\rho-\theta)^2+4\theta\tau\gamma} + (\theta+\rho)\right]$$

$$f_1 = \delta^2 - (\theta+\rho)\delta + (\theta\rho - \theta\tau\gamma)$$

$$f_2 = m_1^2 + (\theta+\rho)m_1 + (\theta\rho-\theta\tau\gamma)$$

$$f_3 = m_2^2 + (\theta+\rho)m_2 + (\theta\rho-\theta\tau\gamma)$$

$$\Delta_2 = (n_2+\theta)e^{n_1T} - (n_1+\theta)e^{n_2T}$$

$$\begin{aligned}e_1 =& \frac{\tau\gamma(\alpha-\beta p)}{\rho-\gamma\tau} - \gamma S_0 - \eta(p-r_0) + \frac{\eta(r_0-p)(\delta-\rho)(\delta-\theta)}{f_1}\\ &+ \frac{c_1\gamma(m_1+\theta)}{k_1f_2} + \frac{c_2\gamma(m_2+\theta)}{k_1f_3} - \frac{\gamma(p\theta+h)}{\theta(\rho-\tau\gamma)^2}\end{aligned}$$

$$\begin{aligned}e_2 =& \frac{\rho(\alpha-\beta p)}{\theta(\rho-\tau\gamma)} - \frac{\eta(r_0-p)(\delta-\rho)e^{-\delta T}}{f_1} + \frac{\gamma}{k_1}\left[\frac{c_1e^{m_1T}}{f_2} + \frac{c_2e^{m_2T}}{f_3}\right.\\ &\left.+ \frac{\gamma(p\theta+h)}{\theta^2(\rho-\tau\gamma)^2}\right]\end{aligned}$$

$$d_1 = \frac{1}{\Delta_2}\left[e_2(n_2+\theta) - e_1e^{n_2T}\right]$$

$$d_2 = \frac{1}{\Delta_2}\left[e_1e^{n_1T} - e_2(n_1+\theta)\right]$$

**Proposition 2**. For a given price p, the preservation technology investment u, and the length of replenishment cycle T; the optimal inventory level($I(t)$) and GCL($G(t)$) are obtained by the following Equations (17) and (18):

$$\begin{aligned}I(t) =& d_1e^{n_1t} + d_2e^{n_2t} - \frac{\rho(\alpha-\beta p)}{\theta(\rho-\tau\gamma)} + \frac{\eta}{f_1}(r_0-p)(\delta-\rho)e^{-\delta t}\\ &- \frac{\gamma}{k_1}\left(\frac{c_1e^{m_1t}}{f_2} + \frac{c_2e^{m_2t}}{f_3} + \frac{\gamma(p\theta+h)}{\theta^2(\rho-\tau\gamma)^2}\right)\end{aligned} \tag{17}$$

$$\begin{aligned}\gamma G(t) =& \frac{\gamma\tau(\alpha-\beta p)}{\rho-\tau\gamma} - (\theta+n_1)d_1e^{n_1t} - (\theta+n_2)d_2e^{n_2t}\\ &- \eta(r_0-p)e^{-\delta t}\left(1-\frac{(\delta-\rho)(\delta-\theta)}{f_1}\right) + \frac{\gamma^2(p\theta+h)}{k_1\theta(\rho-\tau\gamma)^2}\\ &+ \frac{c_1\gamma e^{m_1t}(m_1+\theta)}{k_1f_2} + \frac{c_2\gamma e^{m_2t}(m_2+\theta)}{k_1f_3}\end{aligned} \tag{18}$$

**Proof:** Eliminating G(t) from Equations (2) and (3), and using Equations (14) and (15), one may obtain the differential equation

representing the inventory level as given below:

$$\left[D^2+(\theta+\rho)D+\theta(\rho-\tau\gamma)\right]I(t)=-\rho(\alpha-(\beta+\eta)p)-\eta\delta p+\eta(\delta-\rho)r(t)-\frac{\gamma\lambda_3}{k_1} \quad (19)$$

After solving Equation (16), the optimal path representing the inventory level in the entire replenishment cycle is obtained by the following equation:

$$I(t)=d_1e^{n_1t}+d_2e^{n_2t}-\frac{\rho(\alpha-\beta p)}{\theta(\rho-\tau\gamma)}+\frac{\eta}{f_1}(r_0-p)(\delta-\rho)e^{-\delta t}-\frac{\gamma}{k_1}\left(\frac{c_1e^{m_1t}}{f_2}+\frac{c_2e^{m_2t}}{f_3}+\frac{\gamma(p\theta+h)}{\theta^2(\rho-\tau\gamma)^2}\right)$$

where $d_1$ and $d_2$ are arbitrary constants. Substituting $I(t)$ in Equation (2), one can obtain,

$$\gamma G(t)=\frac{\gamma\tau(\alpha-\beta p)}{\rho-\tau\gamma}-(\theta+n_1)d_1e^{n_1t}-(\theta+n_2)d_2e^{n_2t}-\eta(r_0-p)e^{-\delta t}\left(1-\frac{(\delta-\rho)(\delta-\theta)}{f_1}\right)+\frac{\gamma^2(p\theta+h)}{k_1\theta(\rho-\tau\gamma)^2}+\frac{c_1\gamma e^{m_1t}(m_1+\theta)}{f_2}+\frac{c_2\gamma e^{m_2t}(m_2+\theta)}{f_3}$$

Using the conditions $G(0)=G_0$ and $I(T)=0$, one can find the value of constants, $d_1$ and $d_2$ given above. The proof is complete.

Note that the GCL at the end of the replenishment cycle must be non-negative, i.e. $G(T)\geq 0$. Using Equation (17), the replenishment quantity $I_0$ is obtained as follows:

$$I_0=\frac{1}{\Delta_2}\left[e_2(n_2-n_1)-e_1\left(e^{n_2T}-e^{n_1T}\right)\right]-\frac{\rho(\alpha-\beta p)}{\theta(\rho-\tau\gamma)}+\frac{\eta(r_0-p)(\delta-\rho)}{f_1}-\frac{\gamma}{k_1}\left[\frac{c_1}{f_2}+\frac{c_2}{f_3}+\frac{\gamma(p\theta+h)}{\theta^2(\rho-\tau\gamma)^2}\right] \quad (20)$$

From the above Equation (19), one can observe that $I_0$ is a function of p, u, and T. Obviously, the objective function J defined in Equation (6), is also a function of p, u, and T. Therefore, the following optimization problem based on Equation (21) is required to make an optimal decision:

$$\text{Maximize } \Pi=p[\alpha-(\beta+\eta)p]-\frac{(A+cI_0+u)}{T}+\frac{J}{T} \quad (21)$$

$$\text{Subject to } G(T)\geq 0, p\geq\Gamma, u\geq 0, p\geq c, T\geq 0.$$

It should be mentioned that by calculating the values of $J(p,u,T)$ and $I_0(p,u,T)$, one can obtain the value of the objective function ($\Pi$) for any given $(p,u,T)$. Due to the complexity and nonlinear characteristics of both the objective function (21) and first two constraints related to Equations (15) and (18), it is very difficult to get the optimum solution via an analytical approach. Moreover, the variable corresponding to preservation technology is involved in both the objective function and constants. To obtain the optimal decision from this complex real-world problem, scholars have used algorithms inspired by nature (e.g., Taleizadeh et al., 2013; Sadeghi et al., 2014). In this paper, an SA algorithm is applied to find the solution to the above optimization problem. The SA algorithm was introduced by Kirkpatrick et al. (1983) and it imitates the process of metal annealing. Several authors ( Arostegui et al., 2006; Yeh and Fu, 2007) have pointed out that SA is an optimized method, which has a superior process to obtain global optimal solution. It has been applied widely in almost every area of optimization (Koulamas et al., 1994; Yang, 2014). The SA algorithm for a minimization problem whose objective function is $\pi$, start with an initial solution at a high temperature ($t_0$), and makes a number of changes according to annealing schedules. Any better move that decreases the value of the objective function $\pi$ will be accepted; however, some changes that increase $\pi$ will also be accepted with a probability $prob=e^{-\Delta\pi/k_Bt}$, where $\Delta\pi=\pi_{new}-\pi_{old}$ and $k_B$ is the Boltzmann's constant. $\pi_{new}$ and $\pi_{old}$ represent the value of the objective function at two iterations and t represents the present annealing temperature. Whether a change is acceptable, it depends on a threshold random number r. If $prob>r$ holds, then the change is accepted. As the cooling proceeds to the set frozen point ($t_{min}$), the algorithm terminates (Kang and Zhu, 2016). A brief description of the SA algorithm used to solve the nonlinear constraint optimization problem is presented in the Appendix - A.

## 4. Computational experiments

In this section, numerical examples are considered to get insights of the proposed model. Additionally, a sensitivity analysis is also carried out to examine the effect of changes in parameters on the optimal solution. The following parameter values are considered: $\alpha=200$, $\beta=5$, $\gamma=0.3$, $\rho=0.1$, $\delta=0.25$, $\eta=0.4$, $\tau=0.15$, $\theta_0=0.4$, $\theta(u)=\theta_0e^{-\xi u}$, $\xi=0.05$ $S_0=10$, $r_0=20$, $h=\$1.5$/perunit/week, $c=\$10$/unit, $k_1=1$, and $A=\$200$. The parameters related to preservation technology are considered based on previous studies (e.g., Dye and Hsieh, 2012; Xue et al., 2016). The parameter related to the SA algorithm based on some preliminary parametric studies (Yang, 2014) are considered as follows: $t_0=1.0$, $t_{min}=10^{-9}$, $\alpha_1=0.95$, and $k_B=50$.

Graphical representation of the profit function for above parameter values with respect to two variables for an arbitrary value of third variable are depicted in Fig. 1 a, b, and c:

From above Fig. 1a and b, and c, one can observe that the profit function is concave and there exists a unique optimal solution. By solving problem (20) with an SA algorithm, the optimal decision of the proposed model is obtained as $T=2.24$ weeks, $u=\$76.51$/week, $I_0=170.24$ units, $p=\$25.73$/unit, and corresponding optimal profit per unit time $\Pi=\$888.64$/weeks. The optimal investment in green operations, GCL and reference price effects are governed by the following equations:

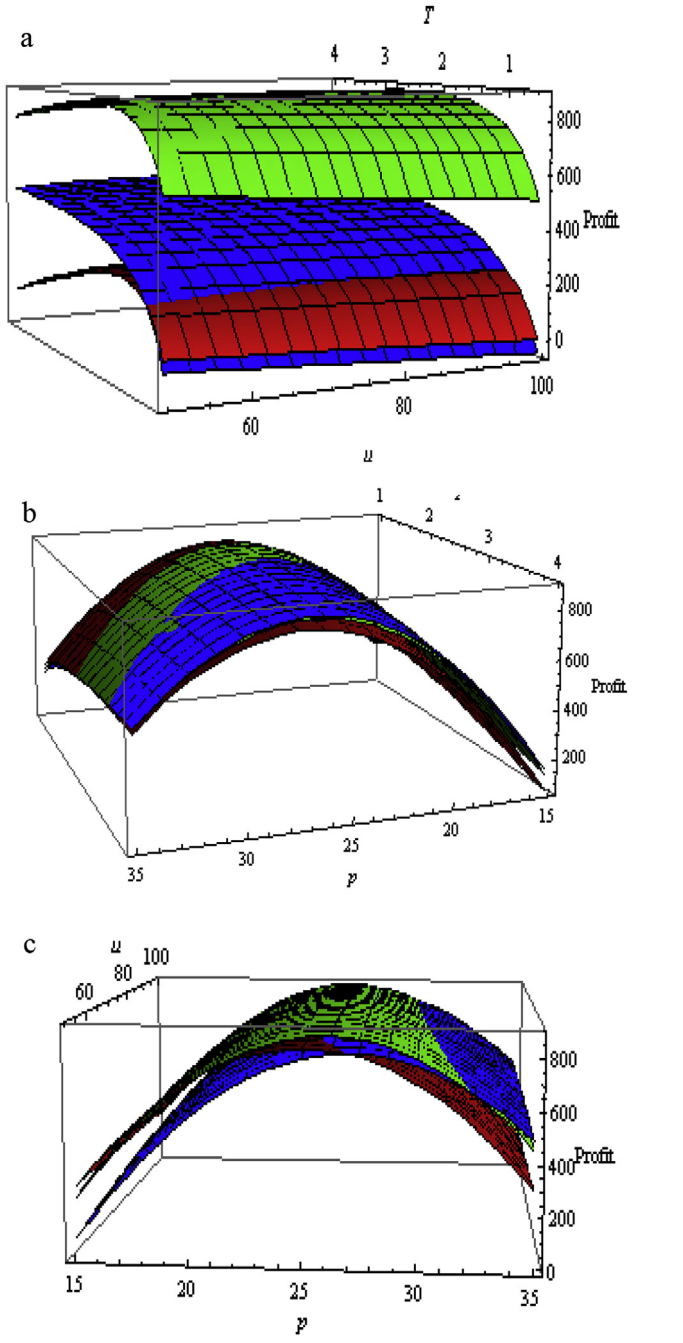


**Fig. 1.** **(a)** Concavity of the profit function with respect to {u, T} for p = {15,25,35}. **(b)** Concavity of the profit function with respect to {p, T} for u = {50,70,90}. **(c)** Concavity of the profit function with respect to {p, u} for T = {1,2.5,4}.

$$g(t) = 1078.32 - 1050.07e^{0.004t} - 13.73e^{0.104t}$$

$$G(t) = 19800.15 - 0.08e^{-0.25t} - 585.51e^{-0.11t} - 5165.51e^{-0.005t} - 13970.61e^{0.005t} - 68.46e^{0.11t}$$
$$r(t) = 25.73 - 5.73e^{-0.25t}$$

Graphical representation of the investment in green operations, GCL and reference price effects are depicted in Fig. 2.

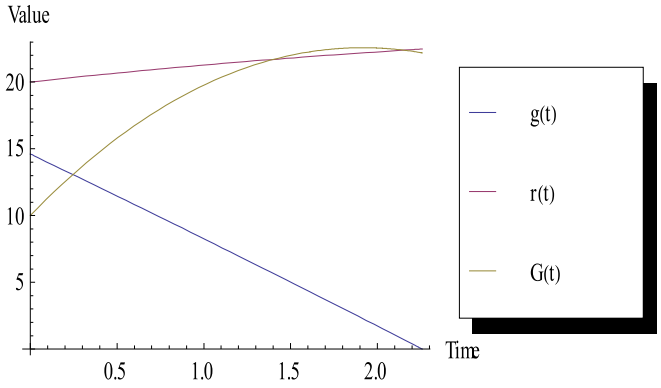


**Fig. 2.** Graphical representation of g(t), r(t) and G(t) for t ε (0,T).

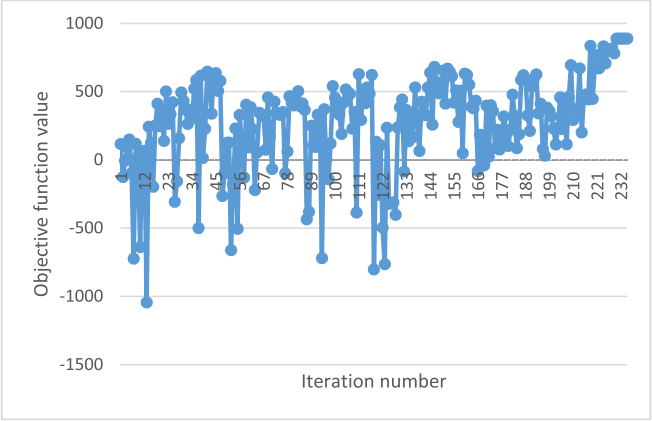


**Fig. 3.** Convergence indicator in improving solution.

From Fig. 2, one sees that the optimal solution satisfies all the conditions. Moreover, the investment in green operations decreases gradually until it reaches zero at the end of the cycle. This result emerges because, at the beginning of the replenishment cycle the on-hand inventory level is relatively high, so the retailer should maintain a high investment level to proliferate its impact on customer' demand. Fig. 2 also shows that the GCL is increasing gradually due to a high initial investment in green operations, which increases consumer awareness; however, due to the decay effect and decreasing investment rate, the GCL decreases after a certain period of time, and in the end, the outcome is $G(T) = 21.95$. Therefore, the investment creates an induction effect to enhance the demand of the product throughout the replenishment cycle.

Fig. 3 pointers the objective function value obtains at different stages of the SA algorithm. At the initial stages, due to high temperature, the SA algorithm accepts nearly all solutions and acts like a random search. The objective function value corresponds to the possible solutions changes in a wide range as seen in Fig. 3. As the temperature decreases, the probability of accepting inferior solutions also declines, the search becomes greedy, only better

**Table 1**
Sensitivity analysis with respect to demand parameters.

| | $T$ | $p$ | $u$ | $I_0$ | $\Pi$ | | $T$ | $p$ | $u$ | $I_0$ | $\Pi$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\alpha = 180$ | 2.33 | 23.87 | 75.25 | 153.66 | 629.36 | $\gamma = 0.2$ | 2.21 | 25.54 | 74.98 | 159.52 | 873.65 |
| $\alpha = 200$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 | $\gamma = 0.3$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 |
| $\alpha = 220$ | 2.16 | 27.59 | 77.76 | 186.48 | 1186.54 | $\gamma = 0.4$ | 2.30 | 25.98 | 78.58 | 180.18 | 905.29 |
| $\alpha = 240$ | 2.11 | 29.45 | 79.02 | 203.01 | 1522.86 | $\gamma = 0.5$ | 2.43 | 26.35 | 82.57 | 197.94 | 924.21 |
| $\beta = 4$ | 2.43 | 30.52 | 82.20 | 199.74 | 1340.36 | $\eta = 0.3$ | 2.23 | 25.87 | 76.36 | 169.02 | 894.94 |
| $\beta = 5$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 | $\eta = 0.4$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 |
| $\beta = 6$ | 2.21 | 22.54 | 74.02 | 154.55 | 593.27 | $\eta = 0.5$ | 2.24 | 25.58 | 76.65 | 170.97 | 882.57 |
| $\beta = 7$ | 2.20 | 20.27 | 72.63 | 140.66 | 389.13 | $\eta =$v0.6 | 2.25 | 25.44 | 76.76 | 171.85 | 876.71 |

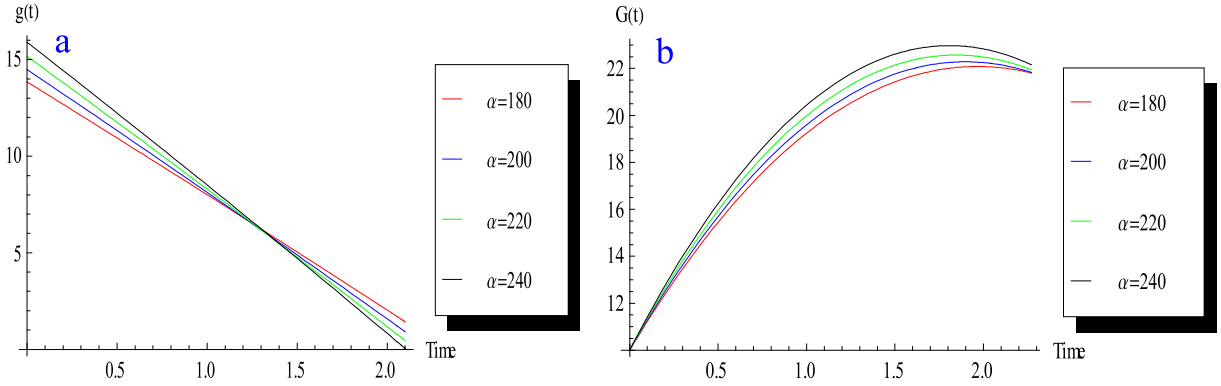


**Fig. 4.** **(a)** Investment in green operations. **(b)** GCL with respect to $\alpha$ with respect to $\alpha$.

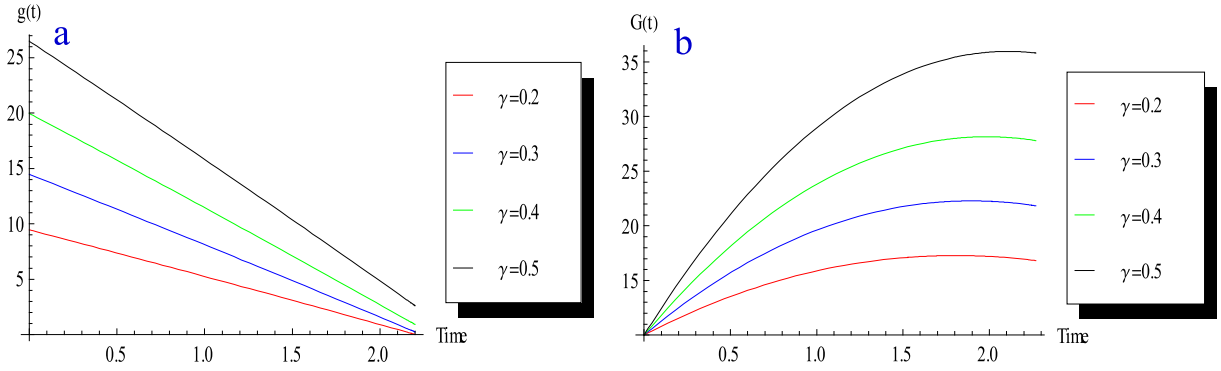


**Fig. 5.** **(a)** Investment in green operations. **b)** GCL with respect to $\gamma$ with respect to $\gamma$.

solutions are accepted and the search finally provides the optimal solution.

Note that if the values of all the parameters related to green operations are equal to zero, i.e. $S_0 = \tau = \gamma = \rho = k_1 = 0$, then the optimal solution is obtained as $T = 2.21$ weeks, $u = \$73.56$/week, $I_0 = 160.45$ units, $p = \$25.31$/unit, and the corresponding optimal profit per unit time $\Pi = \$847.48$/weeks. It shows that the investment in green operations is profitable for the retailer for the above parameter values. Similarly if $S_0 = 0$, i.e. the retailer wishes to invest in green operations from the present cycle, then the optimal solution is obtained as $T = 2.29$ weeks, $u = \$77.16$/week, $I_0 = 170.92$ units, $p = \$25.79$/unit, and the corresponding optimal profit per unit time $\Pi = \$851.42$/weeks. By comparing optimal solutions, one can conclude that the continuous investment in green operations is profitable for the retailer. Moreover, if $\gamma = 0.1$, $S_0 = 0$, $k_1 = 2$, and $\rho = 0.6$, i.e. customers are not sensitive enough for green operations and the retailer is not effective in investment, then one can obtain the following optimal solution $T = 2.22$ weeks, $u = \$74.09$/week, $I_0 = 164.39$ units, $p = \$25.15$/unit, and the corresponding optimal profit per unit time $\Pi = \$846.98$/weeks. In these circumstances, the investment is not profitable for the retailer and the profit per unit time is reduced marginally. Next, the sensitivity analysis is carried out with respect to all the parameters used to develop the model. When the value of one parameter varies, the others remain unchanged.

As shown in Table 1, an increasing market potential will lead to increasing $p$, $u$, $I_0$, and $\Pi$. This finding implies that the retailer has an opportunity to invest more in preservation technology and green operations (Fig. 4a) when the market potential is high. Due to the higher investment, the GCL is also increased (Fig. 4b). A high market potential will force the retailer to set a high price, which provides a greater investment opportunity. The relatively low replenishment cycle is mainly caused by the higher demand rate. Similarly, a high GCL sensitivity stimulates the retailer to invest more in green operations. Table 1 shows that an increasing

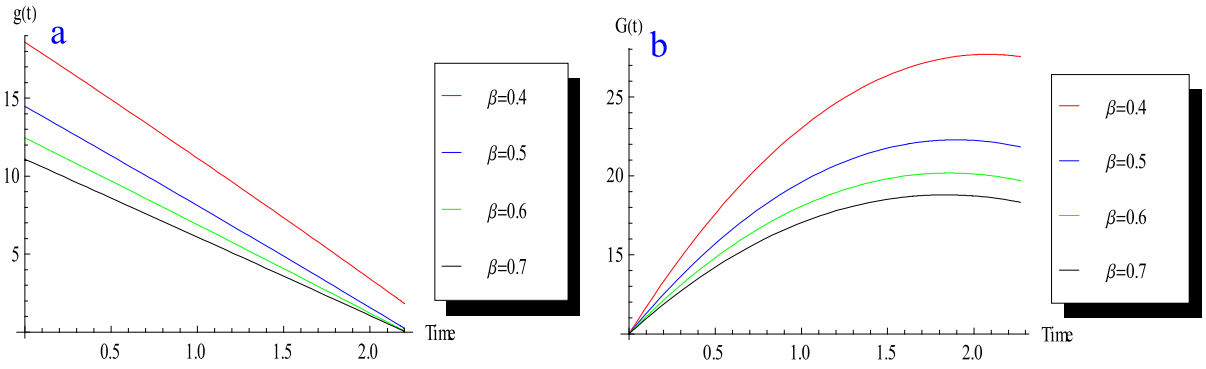


Fig. 6 Investment in green operations with respect to β

Fig. 6 GCL with respect to β

**Fig. 6.** **(a)** Investment in green operations. **(b)** GCL with respect to β with respect to β.

**Table 2**
Sensitivity analysis with respect to parameters related to dynamics of GCL and reference price.

| | $T$ | $p$ | $u$ | $I_0$ | $\Pi$ | | $T$ | $p$ | $u$ | $I_0$ | $\Pi$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $G_0 = 5$ | 2.26 | 25.61 | 76.84 | 170.53 | 869.93 | $\theta_0 = 0.3$ | 2.21 | 25.71 | 70.19 | 167.81 | 891.23 |
| $G_0 = 10$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 | $\theta_0 = 0.4$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 |
| $G_0 = 15$ | 2.21 | 25.84 | 76.18 | 169.55 | 907.56 | $\theta_0 = 0.5$ | 2.26 | 25.74 | 81.39 | 172.11 | 886.66 |
| $G_0 = 20$ | 2.18 | 25.95 | 75.85 | 169.14 | 926.68 | $\theta_0 = 0.6$ | 2.28 | 25.75 | 85.38 | 173.45 | 884.05 |
| $\tau = 0.05$ | 2.23 | 25.74 | 75.57 | 170.01 | 889.05 | $\delta = 0.2$ | 2.22 | 25.69 | 76.29 | 169.27 | 887.41 |
| $\tau = 0.15$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 | $\delta = 0.25$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 |
| $\tau = 0.25$ | 2.24 | 25.73 | 77.41 | 170.34 | 888.25 | $\delta = 0.3$ | 2.25 | 25.75 | 76.69 | 170.74 | 889.57 |
| $\tau = 0.35$ | 2.25 | 25.72 | 78.27 | 170.56 | 887.88 | $\delta = 0.35$ | 2.26 | 25.79 | 76.86 | 171.18 | 890.91 |
| $r_0 = 15$ | 2.30 | 25.62 | 77.53 | 173.01 | 867.24 | $\rho = 0.05$ | 2.27 | 25.77 | 77.25 | 172.96 | 891.06 |
| $r_0 = 20$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 | $\rho = 0.1$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 |
| $r_0 = 25$ | 2.17 | 25.84 | 75.50 | 167.07 | 910.43 | $\rho = 0.15$ | 2.21 | 25.69 | 75.88 | 167.65 | 886.44 |
| $r_0 = 30$ | 2.11 | 25.96 | 75.41 | 164.30 | 932.61 | $\rho = 0.2$ | 2.19 | 25.65 | 75.35 | 165.59 | 884.42 |

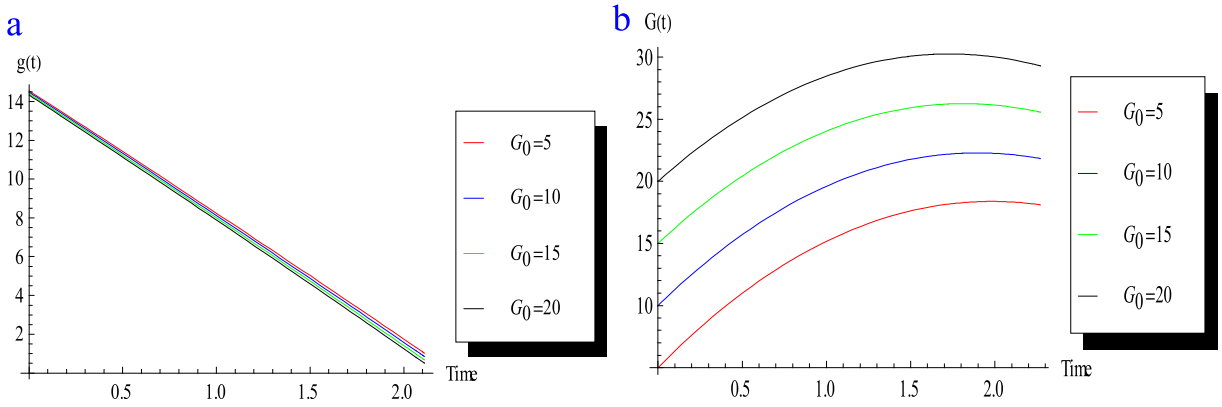


**Fig. 7.** **(a)** Investment in green operations. **(b)** GCL with respect to $G_0$ with respect to $G_0$.

γ leads to increasing $I_0$, $p$, and Π; this finding encourages the retailer to invest more in green operations (Fig. 5a and b) (to maintain a high GCL), and in preservation technology (to minimize the partial influence of item deterioration). This finding is also consistent with the recent empirical study by Kwong and Balaji (2016) where the authors argue that the customers' environmental attitude and subjective-specific cognitions are important features for promoting green products. However, when parameters related to price and reference price change, the other parameters vary also. Therefore, this price sensitivity reduces the opportunity to set a high price. When $\beta$ increases, the optimal Π, $u$, $I_0$, and $p$ decrease. The results in Table 1 also justify these intuitive findings. Moreover, Fig. 6a and b, show that the retailer should invest less in green operations; that is, the enthusiasm of consumers affects the benefit of retailer investments in green operations, and sometimes, consumer expectations for green operations and the cost-effective price of the product hurt the retailer. The retailer should set a low selling

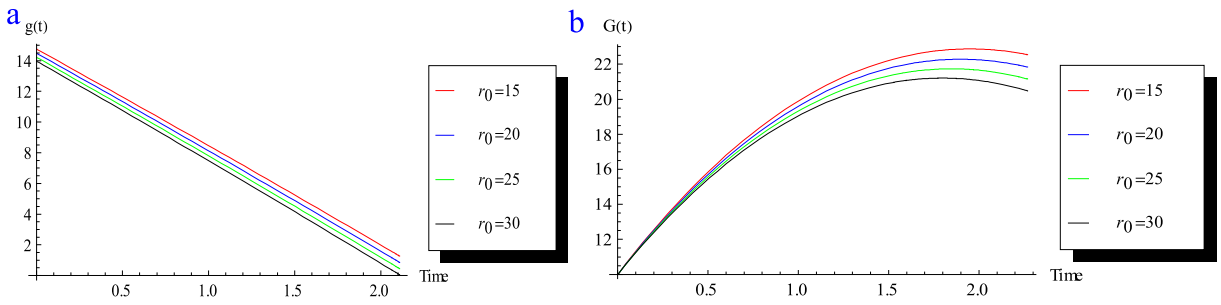


**Fig. 8.** **(a)** Investment in green operations. **(b)** GCL with respect to $r_0$ with respect to $r_0$.

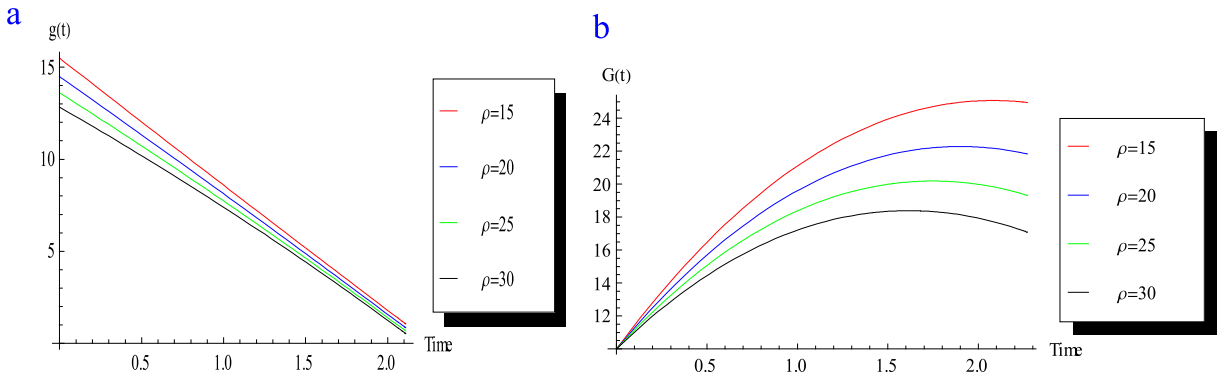


**Fig. 9.** **(a)** Investment in green operations. **(b)** GCL with respect to ρ with respect to ρ.

**Table 3**
Sensitivity analysis with respect to cost parameters.

| | $T$ | $p$ | $u$ | $I_0$ | Π | | $T$ | $p$ | $u$ | $I_0$ | Π |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $c = 5$ | 2.01 | 23.17 | 66.53 | 188.11 | 1320.17 | $h = 1.0$ | 2.90 | 25.72 | 87.55 | 225.21 | 939.31 |
| $c = 10$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 | $h = 1.5$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 |
| $c = 15$ | 2.27 | 28.23 | 80.31 | 143.69 | 541.32 | $h = 2.0$ | 1.89 | 25.77 | 69.47 | 141.34 | 850.51 |
| $c = 20$ | 2.28 | 30.71 | 80.39 | 126.75 | 259.02 | $h = 2.5$ | 1.67 | 25.84 | 64.28 | 123.44 | 817.87 |
| $\xi = 0.04$ | 2.27 | 25.76 | 91.05 | 173.17 | 880.38 | $k = 0.8$ | 2.26 | 25.78 | 77.14 | 173.13 | 899.94 |
| $\xi = 0.05$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 | $k = 1.0$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 |
| $\xi = 0.06$ | 2.21 | 25.71 | 66.30 | 166.66 | 894.49 | $k = 1.2$ | 2.22 | 25.69 | 76.11 | 168.01 | 880.81 |
| $\xi = 0.07$ | 2.18 | 25.68 | 58.71 | 165.86 | 898.87 | $k = 1.4$ | 2.21 | 25.66 | 75.82 | 166.75 | 877.21 |
| $A = 180$ | 2.13 | 25.67 | 74.51 | 162.23 | 897.79 | | | | | | |
| $A = 200$ | 2.24 | 25.73 | 76.51 | 170.24 | 888.64 | | | | | | |
| $A = 220$ | 2.33 | 25.78 | 78.34 | 177.64 | 879.89 | | | | | | |
| $A = 240$ | 2.43 | 25.83 | 80.03 | 184.41 | 871.49 | | | | | | |

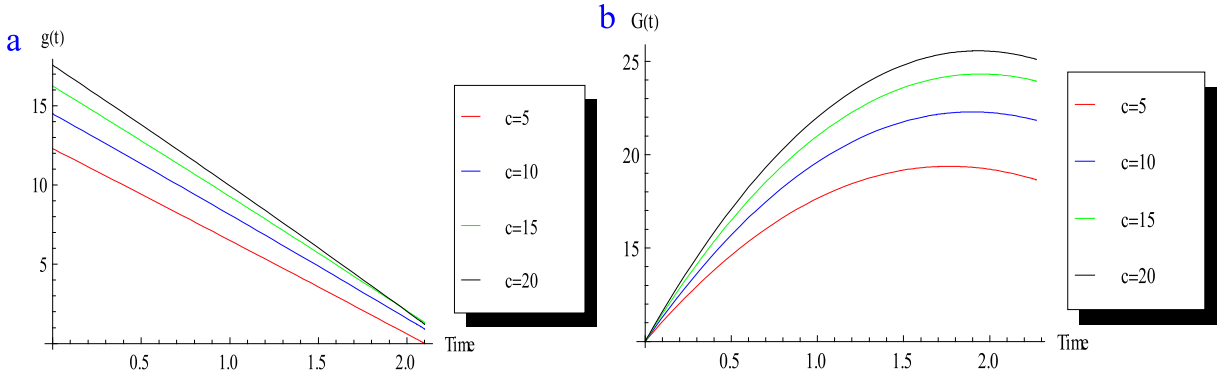


**Fig. 10.** **(a)** Investment on green operations. **(b)** Green concern level with respect to c.

price to increase demand when the reference price effect is large. Therefore, as shown in Table 1, an increasing reference price effect leads to decreasing Π. The price shows a steady increase due to the exponential smoothing effect of the parameter $\eta$. The retailer invests less in green operations when the value of $\eta$ is high. In a recent empirical study, Chekima et al. (2016) reported that man's nature significantly influences the green purchase intention. The result of the analysis is consistent with those from the market survey. Apart from market potential, price and GCL sensitivities are two important factors influencing the profitability of the retailer.

Continuous investment in green operations is always worthwhile for the retailer. Therefore, as shown in Table 2, a high initial GCL leads to high $p$ and Π. Fig. 7a and b shows that the retailer will invest less in green operations due to a high initial GCL at the end of the previous cycle. The preservation technology investment and the replenishment cycle time are also reduced due to the higher demand induced by the initial GCL. Therefore, the retailer should invest in green operations for profitability not only for the present replenishment cycle but also for the future. From Table 2, one observes that when $\theta_0$ increases, the optimal Π decreases and the optimal $T$, $I_0$, $u$, and $p$ increases. This finding suggests that when the natural deterioration rate is relatively high, the retailer should invest more in preservation technology to maintain sustainability. The retailer also needs to order more product for satisfying market demand. Moreover, the retailer should increase the price of the product to compensate for the high investment in preservation technology and a high natural deterioration rate that will lead to low profits. Results also show that the retailer's is relatively less sensitive with respect to the memory parameter. The initial reference price has a substantial effect on the pricing and profitability of the retailer. A high initial reference price always enhances the flexibility of the retailer for setting the price. Table 2, shows that an increasing $r_0$ leads to increasing $p$ and Π. From Fig. 8a and b, one can observe that the retailer invests less in green operations when initial reference prices are relatively high due to higher demand. Therefore, customer expectations are a stimulating factor for investments in green operations. The selling period is shortened with the increasing decay rate of the investment. As a consequence, Table 2 shows that an increasing decay rate leads to decreasing $p$, $u$, $I_0$, and Π. Fig. 9a and b shows that the retailer invests less in green operations when the decay rate is high. If more retailers intend to invest in green operations, a comparative assessment of consumers may lead to a high decay rate. In this circumstance, for maximizing the investment effect, the retailer should decrease the order quantity as well as the price to reduce the length of the replenishment cycle. A high decay rate on investment will lead to low profit.

Table 3 shows that an increasing purchasing cost leads to increasing $p$ and $u$, while the optimal $I_0$ and Π will decrease. Because a relatively high purchasing cost means the product is more valuable, the retailer should decrease the order quantity and charge a high sales price to mitigate the loss caused by the increased unit cost. The retailer should invest more in preservation technology to reduce the deterioration rate. The long replenishment cycle is mainly caused by the small demand rate. Fig. 10a and b show that the retailer's investment in green operations is significantly sensitive to the unit cost of the product. The retailer should invest more in the product with the higher unit cost. Similarly, once the holding cost $h$ per unit time increases, the optimal sales price $p$ increases marginally while the optimal $T$ and Π decrease significantly. The retailer should decrease its order quantity and accordingly shorten the replenishment cycle. In addition, the retailer's funding for the preservation technology and green operations declines due to the high operations cost, which is the other reason for the significantly shortened replenishment cycle. Fig. 11a and b also explain the consequence. High investment efficiency implies that the retailer is maintaining cost-effective operations. Therefore, when $\xi$ increases, the optimal Π increases, while the optimal $T$, $I_0$, and $u$ decrease; the results of the sensitivity analysis in Table 3 justify this intuitive conclusion. A relatively small $\xi$ suggests a relatively high marginal cost per unit sales such that, to maximize profit, the retailer should charge a relatively high sales price for a small value of $\xi$. The results obtained with the sensitivity analysis also support this pricing strategy. Moreover, the retailer should invest in green operations to maintain higher GCLs for smaller values of $\xi$. An increasing green operations investment coefficient implies poor outcomes; that is, the investment harms the profitability of the retailer. The sensitivity analysis of the model presented in Table 3 supports this conclusion. As $k_1$ increases, the optimal $p$, $T$, $I_0$, $u$, and Π decrease. This result encourages the retailer to reduce investment in preservation technology. In addition, the GCL decreases significantly as $k_1$ increases (Fig. 12a and b), and the retailer should set a lower sales price to stimulate demand due to the decreasing GCL. Table 3 indicates that the optimal $p$, $T$, $I_0$, and $u$ will increase with an increase in $A$ while the optimal Π will decrease. This finding implies that if the replenishment cost per order is high, the retailer will order a large quantity to reduce the replenishment cost. When $A$ is large, the retailer tends to increase preservation technology and green operations

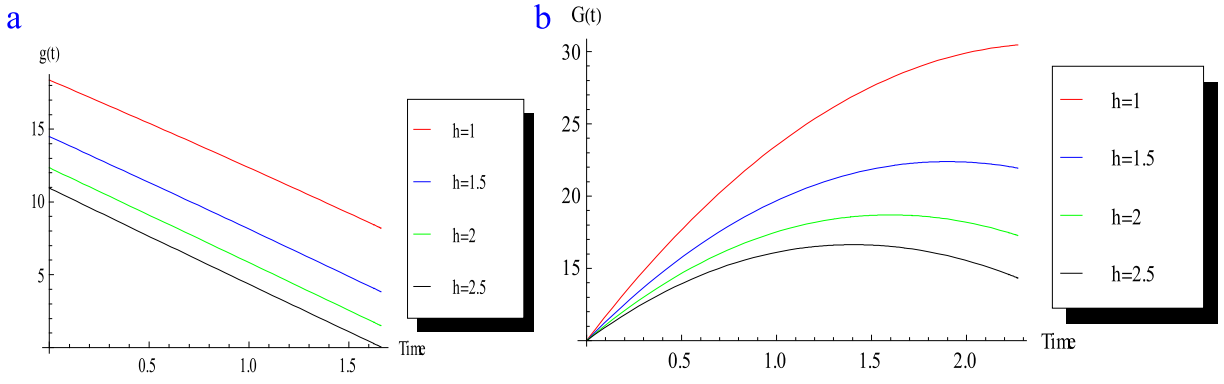


**Fig. 11.** **(a)** Investment on green operations. **(b)** Green concern level with respect to h.

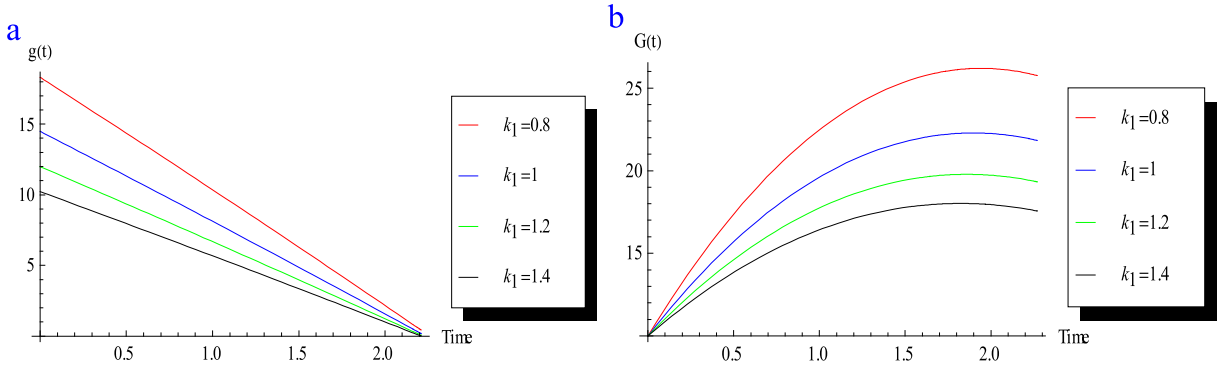


**Fig. 12.** **(a)** Investment on green operations. **(b)** Green concern level with respect to $k_1$.

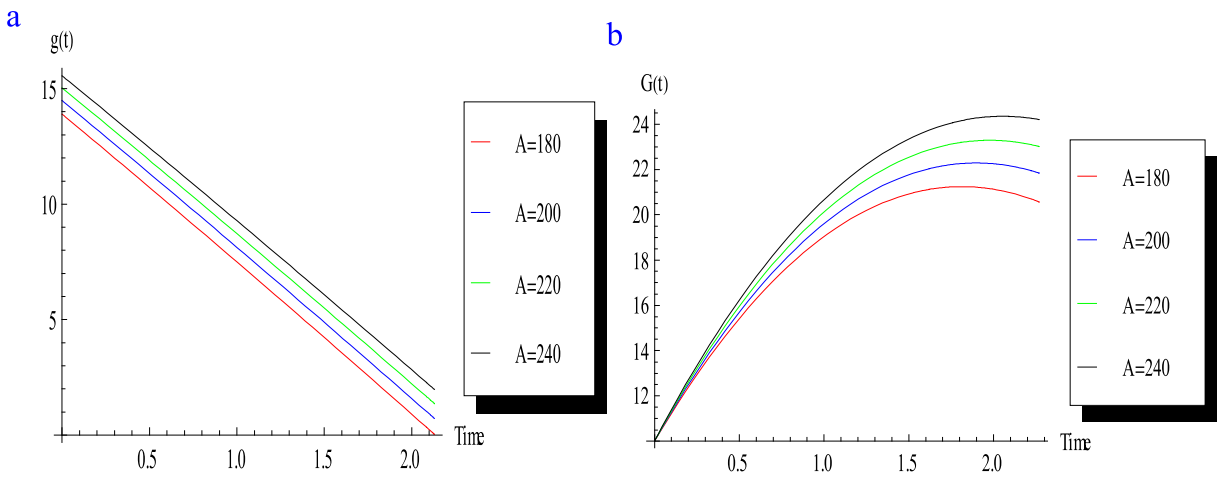


**Fig. 13.** **(a)** Investment on green operations. **(b)** Green concern level with respect to A.

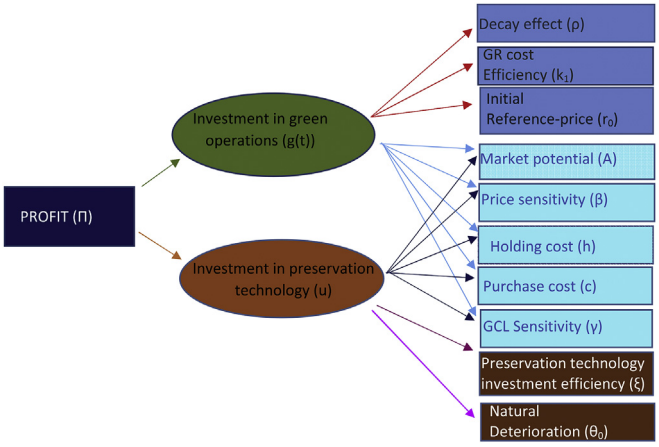


**Fig. 14.** Impact of parameter values on the investment decisions and optimal profit.

investments (Fig. 13a and b) to reduce the deterioration of the inventory. These actions extend the replenishment cycle. In addition, the retailer will increase the sales price to compensate for the high operational cost.

Summarizing the study results, it is concluded that the GCL is highly sensitive to the following parameters: $\gamma$, $\beta$, $\rho$, $G_0$, $c$, $h$, $k_1$, and $A$. Similarly, the retailer's investment in preservation technology is sensitive to the following parameters: $\beta$, $\theta_0$, $\gamma$, $c$, $h$, and $\xi$. Finally the total retailer profit is highly sensitive to the following parameters: $\alpha$, $\beta$, $\gamma$, $r_0$, $G_0$, $c$, and $h$; that is, the product value is an important factor for both investment decisions. The corresponding graphical representation is depicted in Fig. 14.

Investment in green operations helps retailers to improve their competitive position in the marketplace. This study provides an analytical measurement that can serve as a procedure to evaluate important factors influencing investment decisions in green operations and preservation technology, which are integral to a retailer sustainability program. In an empirical study on the automobile and furniture industries, De Medeiros and Ribeiro (2016) found that

the retailer can mitigate financial and social risks by promoting green products. The results of this study also demonstrated that the investment in green operations of the retailer creates considerable impact on profitability. However, the results also suggest that both retailer and consumer characteristics significantly drive investment in green operations. The retailer's own investment efficiency and the consumer reference price both play a significant role in motivating the retailer to invest in green operations. To enhance profit, retailers need to design an investment plan that can make an impact in the long term to reduce the decay effect and must determine the best way to enhance consumer awareness level. Therefore, the retailer needs to undertake a consumer research program and gain feedback on the consumers' level of interest in green operations consistently through in-store posters, demonstrations and workshops, sales associates, brochures, newsletters, website and others.

## 5. Summary and concluding remarks

This paper analyzes a decision-making problem for a retailer to determine the sales price, dynamic investment levels in green operations and preservation technology, and replenishment time. The impact of the reference price is considered in maximizing the total profit per unit time. Pontryagin's maximum principle and an SA algorithm are used simultaneously to find the optimal decision. The results in this paper offer theoretical contributions and suggest managerial implications. First, this is the first study in which the dynamics of green operations investment and its impacts are studied analytically. With such a decision model, the retailer can implement better pricing strategies and make green operations investment decisions. Second, the analytical solutions related to dynamic green operations and preservation technology investments, as obtained through the use of Pontryagin's maximum principle combined with the SA algorithm, serve as powerful tools for making replenishment decisions when the reference price effect is considered. Third, via computational studies, results show that continuous investment in green operations is always profitable for the retailer. Moreover, investment in green operations helps the retailer to enhance the GCL. The reference price of consumers and effectiveness of the retailer are important factors for the retailer to consider before investing in green operations. The retailer's decision to invest in preservation technology as a means to reduce deterioration is also correlated with GCL. Research on this problem can be extended in several ways. For instance, one may impose budgetary restrictions on total investment during a replenishment cycle. In addition, researchers may want to generalize the model to allow for shortages, non-instantaneous item deterioration, disposal cost, and other factors. GCL depends on different product categories and economic conditions; therefore, it will be worthwhile to use surveys to estimate the range of parameter values.

## Acknowledgements

The authors are grateful to valuable comments by five referees to improve earlier versions of the paper. This research was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2015R1A2A1A15053948).

## Appendix

The SA algorithm to solve the above problem is given below:
**Algorithm 1.** Simulated annealing algorithm.

Initialize SA and other system parameters, maximum number of iteration N
Define objective function $\pi(x)$, $x = (p, u, T)^T, x^0$
Define cooling schedule $t \mapsto \alpha_1 t$, $\alpha \in (0, 1)$
while ($t > t_{min}$ and $n < N$)
    Perturb $x_n$ to get a new state $x_{n+1}$ // by using uniform distribution in [-0.1, 0.1]
    Calculate $\Delta\pi$
    Accept the new solution if improved
    if not improved
        Generate a random number $r$
        Accept if $prob > r$ // $r$ is a random number between (0,1)
    end if
    Update the best $x$ and $\pi$
    n=n+1
end while

The penalty method (Deb (2000)) is used to find the solution of the nonlinear optimization problem (p3) with inequality constraints. For the optimization problem

$$\min f(x),\ x = (x_1, x_2, \ldots, x_n)^T \in R^n$$

$$\text{subject to } g_i(x) \leq 0,\ (i = 1, 2, \ldots, N)$$

the pseudo-objective function yielded by using penalty method is $\min f_1(x) = f(x) + \sum_{i=1}^{N} \mu_i g_i^2(x)$ where $\mu_i$ is a non-negative large number, known as the penalty factors.

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