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Coordinating a socially concerned reverse supply chain for pharmaceutical waste management considering government role

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Abstract

This paper deals with statutory antibiotic waste management in a two-echelon sustainable pharmaceutical reverse supply chain. Due to detrimental impacts of improper disposal of unwanted/expired medicines on the environment, governments enact legislation regarding pharmaceutical waste management. According to environmental legislation, the manufacturer needs to collect a certain amount of pharmaceutical waste through a reverse channel. Duopolistic distributors are responsible for the collection process and compete on their return quantity, which depends on corporate social responsibility (CSR) efforts through increasing public consciousness of unwanted/expired antibiotics. In this paper, the effects of distributors' competitive CSR participation on the collected amount of antibiotics and costs of involving members are analytically investigated under decentralized and centralized mathematical models. A new saving-cost sharing contract is then proposed, which is capable of maximizing supply chain's profitability and coordinating both levels of the reverse chain under competition. The results reveal that companies enjoy a considerable monetary benefit, improved social image, and higher sustainability level using the proposed scheme. Moreover, governmental penalties imposed on the companies also remarkably reduce. Therefore, the proposed model is considerably effective in mitigating the environmental pollution associated with pharmaceutical waste disposal.

Keywords Sustainability · Pharmaceutical reverse supply chain · Channel coordination · CSR competition · Saving-cost sharing contract

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1 Introduction

Sustainability has become a popular issue in recent decades (Rajesh & Rajendran, 2020) because of increasing environmental concerns such as carbon emissions, toxic substance consumption, global warming, and resource scarcity (Xie & Breen, 2012). In the pharmaceutical sector, sustainability could be considered as (a) effective waste management, i.e., collecting the expired/unwanted pharmaceuticals to protect the environment and public health from potential detrimental impacts of improperly disposed of medications (Xie & Breen, 2012), and (b) improving public awareness about hazardous pharmaceuticals (Veleva et al., 2003) along with (c) meeting economic goals of shareholders (Koberg & Longoni, 2018; Rajesh, 2020). Accordingly, the reverse flow of pharmaceuticals is a highly significant issue regarding sustainability.

The global amount of unwanted/expired medications has grown over recent years, highlighting the significance of pharmaceutical waste management (Ding, 2018). Since improperly disposed of drugs with chemical hazard potential pose a serious risk to the environment and public health (Daughton, 2003), this issue has increased the international concerns about the potential detrimental impacts of these compounds on surface waters (Batt et al., 2006), groundwaters (Verstraeten et al., 2005), and landfills (Halling-Sørensen et al., 1998). For instance, the entrance of antibiotics in waterways affects the bacteria's existence and may cause antibiotic resistance (Braund et al., 2009). Hence, outdated medical products must be collected and incinerated due to their chemical hazard potential (Kabir, 2013). Due to the aforementioned detrimental impacts of medical leftovers, reverse logistics in the pharmaceutical industry has attracted international attention.

Reverse logistics (RL) contains a set of activities regarding proper disposal or recovery of returned products (Mahmoudi & Fazlollahtabar, 2014). Firms engage in such activities to abide by the government's environmental obligations, to keep up with the recent competitive market (Agrawal et al., 2015; Li et al., 2014), and protect the environment (Sharma et al., 2011). In contrast to the automotive and electronic industries, pharmaceutical RL only aims to prevent harm to the environment and public health; therefore, it is not financially beneficial. Accordingly, granting governmental subsidy (or imposing penalties) to the manufacturers may lessen environmental degradation in reverse channels (Hong et al., 2016). Incentive mechanisms for customers to return their products are critical issues in RL since they dramatically influence the return quantity, the most essential factor in reverse channels. Apart from popular monetary incentives, CSR activities could also increase the customers' motivation to return unwanted items. For instance, a Canadian pharma-manufacturer named "Apotex" implements collection programs as CSR efforts to provide customers a safe and environmentally friendly way to dispose of unused or expired medications.[1] There is often more than a single collector competing on their return quantity in real-world situations, and this competition dramatically affects the number of collected items. To evaluate the effect of CSR on the supply chain, many researchers employed coordination mechanisms to analyze the decision-making and enhance the CSR level (Liu et al., 2019).

Supply chain (SC) coordination has been a popular issue in supply chain management in recent years (De Giovanni, 2016). Under the coordinated system, all SC members are satisfied to shift their decentralized locally optimal decisions to centralized globally optimal ones. In fact, while centralized solutions lead to maximum

[1] http://www.apotex.com, accessed at 18 Nov 2018.

SC performance, some individual participants may incur losses compared to the traditional decentralized structure (Mafakheri & Nasiri, 2013). Thus, various incentive mechanisms are developed to induce different parties to participate in the coordination plan (Hosseini-Motlagh et al., 2019) and ensure that all SC members benefit from SC coordination (Swami & Shah, 2013).

The purposes of this paper are twofold. First, considering a single-manufacturer and duopolistic competing distributors in the pharmaceutical industry, we aim to analyze the distributors' CSR decisions on collecting unwanted medications under the decentralized and centralized models. Moreover, we aim to propose a new method to coordinate distributors' CSR decisions under competition in the reverse flow of the investigated pharmaceutical supply chain, decreasing all members' costs. Accordingly, the main questions that the current study addresses are:

1. How the customers' social awareness, as a CSR effort, affects the collected amount of unwanted medications?
2. What are the members' interactions in a reverse channel when distributors frequently visit customers in the collections process? How can managers deal with the competitive collection and the subsequent conflict of interests between members effectively?
3. Which coordination scheme is acceptable for all members and simultaneously coordinates both chain levels and competing distributors in the reverse flow?
4. How can managers prevent the detrimental impacts of improperly disposed of medications on the environment and public health and deal with the government's regulations?

This paper deals with statutory antibiotic waste management in a two-echelon sustainable pharmaceutical reverse supply chain. In fact, the manufacturer faces environmental legislation to collect a certain level of unwanted medications and prefers to outsource the collection activities to distributors. Duopolistic distributors compete on their corporate social responsibility (CSR) efforts through increasing public consciousness regarding unwanted/expired antibiotics. Although CSR efforts are costly for the distributors, it enhances the collection level of unwanted medications and reduces the manufacturer's cost imposed by the government. Therefore, the distributors' CSR efforts affect their profits, all members' mutual profits, and the entire supply chain performance. To analyze the mentioned sustainable pharmaceutical reverse supply chain (SPRSC), we first study the decentralized decision-making structure, in which the distributors individually determine their CSR participation levels. Then, the centralized system is investigated, in which a single decision-maker tries to optimize CSR participation levels from the entire SPRSC point of view. Finally, we propose a novel coordination contract that satisfies all SPRSC members in terms of costs and raises the CSR levels.

The structure of this paper is as follows. The literature review is presented in "Literature review"Section. In "Problem definition"Section , the definition of the problem and notations are denoted. Model formulations in the decentralized and centralized structures and a coordination mechanism are proposed in "Decision variables"Section. Numerical results for a realistic case and sensitivity analysis are provided in "Parameters" and "Model formulation"Sections, respectively. "Case study"Section contains the final conclusion and future study recommendations.

2 Literature review

This section presents a review of the related literature on pharmaceutical RL and sustainability and then focuses on social issues and supply chain coordination.

2.1 Pharmaceutical RL and sustainability

Because of growing environmental awareness (Ling & Xu, 2020), pharmaceutical companies' sustainability has recently gained international attention (Halim et al., 2019). For instance, Kumar et al. (2019) use fuzzy Delphi approach and fuzzy analytical hierarchy process (AHP) to implement green supply chain principles in the Indian pharmaceutical sector. Basu et al. (2019) explored that the Indian pharmaceutical industry has become more eco-friendly recently, while there is still a huge improvement potential. RL contributes greatly to sustainability as it decreases the amount of harmful waste, causing environmental pollution (Rezaei & Maihami, 2020). As an example in the pharmaceutical RL literature, Narayana et al. (2019) study the role of reverse logistics in the sustainability level of the pharmaceutical industry in India using system dynamics methodology. Hosseini-Motlagh, Nami, et al. (2020) investigate a pharmaceutical closed-loop supply chain that reuses the produced drugs' plastic containers. Taleizadeh et al. (2020) used a robust approach to tackling pharmaceutical RL challenges. Viegas et al. (2019) conducted a literature review on pharmaceutical RL based on end-of-use and end-of-life medicines classification. Hosseini-Motlagh, Jazinaninejad, et al. (2020) apply the supply chain coordination and game theory approaches to tackle the reverse flow of defective pharmaceutical products. Abbas and Farooquie (2018) evaluate practices, drivers, return conditions, and barriers of pharmaceutical RL in Indian retail market. Hosseini-Motlagh, Nematollahi, et al. (2020) coordinate a channel for pharmaceutical recall under stochastic production disruption.

Also, different incentive strategies have been proposed in the literature to increase the volume of collected drugs. For instance, Abbas and Farooquie (2013) state that most customers tend to give back their unwanted medications in exchange for another usable medicine or other bonuses. Weraikat et al. (2016a) state that incentives can motivate the customers to return their leftover medications in the pharmaceutical reverse supply chain. Weraikat et al. (2016b) propose a coordination approach based on negotiation in pharmaceutical RL to coordinate the reverse flow of unwanted medications at customer zones. According to Ding (2018), the pharmaceutical industry's major problems are lack of coordination and cooperation, ineffective waste management, and insufficient public consciousness relative to the importance of sustainability, especially among pharmacists and consumers. Despite the exigency of pharmaceutical RL, studies in this research field are scarce, and also sustainability and social issues have not been noticed in the pharmaceutical RL literature adequately (Ding, 2018). However, this study proposes social efforts as an incentive to augment the return quantity of pharmaceuticals.

2.2 CSR and supply chain coordination

Valuing CSR and social issues is necessary for long-term sustainability, which benefits the communities and enhances the planet's well-being (Kaur & Sharma, 2018). And to evaluate CSR's effect on the supply chain, many researchers employed coordination mechanisms to analyze the decision-making and enhance the CSR level (Liu et al., 2019). For example, Heydari and Mosanna (2018) coordinate a two-layer sustainable supply chain considering consumer social awareness. Also, Hou et al. (2019) apply differential game and coordination approaches to enhance environmental and social sustainability. Zerang et al. (2018) coordinate a closed-loop supply chain with social and environmental concerns and show that coordination boosts system performance compared to the decentralized one. Besides, implementing the revenue-sharing coordination scheme, Gang et al. (2020) motivate Chinese suppliers to improve CSR and greenness level.

Reviewing the previous researches reveals that there are few studies on coordinating the pharmaceutical supply chain with social considerations. Nematollahi et al. (2017) coordinate a socially responsible pharmaceutical SC, consisting of one pharma-manufacturer and one pharma-retailer, under stochastic demand. They illustrate that the coordinated decision-making structure provides both social and economic benefits. Likewise, Nematollahi et al. (2018) develop a multi-objective mathematical model to coordinate visit interval and safety stock level in a socially responsible pharmaceutical SC with consideration of service level. Also, Johari and Hosseini-Motlagh (2020) coordinate pricing and CSR decisions in a pharmaceutical supply chain under competition. These studies focus on the forward flow of pharmaceutical SC. Although Weraikat et al. (2016a) and Weraikat et al. (2016b) examine the reverse flow of unwanted medication using coordination context, they do not consider channel coordination by contracts, competition between collectors, and corporate social responsibility as a strategy for collecting unwanted medications. However, in this paper, we extend the model proposed by Weraikat et al. (2016b) in the pharmaceutical sector and investigate the coordination of two competitive pharma-distributors' CSR decisions on collecting unwanted medications. Accordingly, the main contributions of the current study compared to the previous literature are:

1. Proposing a new saving-cost sharing contract, acceptable for all members and simultaneously coordinates both chain levels and competing distributors in reverse flow.
2. Considering the effect of social awareness as a CSR effort on the collected amount of unwanted medications.
3. Studying competition between distributors on the level of social awareness in reverse flow of pharmaceutical SC in a way that they frequently visit customers to collect unwanted medications.
4. Preventing the detrimental impacts of improperly disposed of medications on the environment and public health under the government's regulations using channel coordination models.

3 Problem definition

Hospitals and pharmacies usually adopt a conservative inventory system, which causes excessive medications to expire due to the absence of demand (Weraikat et al., 2019). In this model, we study the reverse flow of a two-level sustainable pharmaceutical supply chain consisting of a manufacturer and duopolistic competing distributors with the aim of effective waste management. Regarding the environmental health policies, the government imposes an obligation on the manufacturer to collect a minimum amount of unwanted medications from hospitals and pharmacies. If the manufacturer's actual amount of collected unwanted medications is less than the minimum amount, the government imposes a penalty on him. Besides, if the manufacturer collects more than

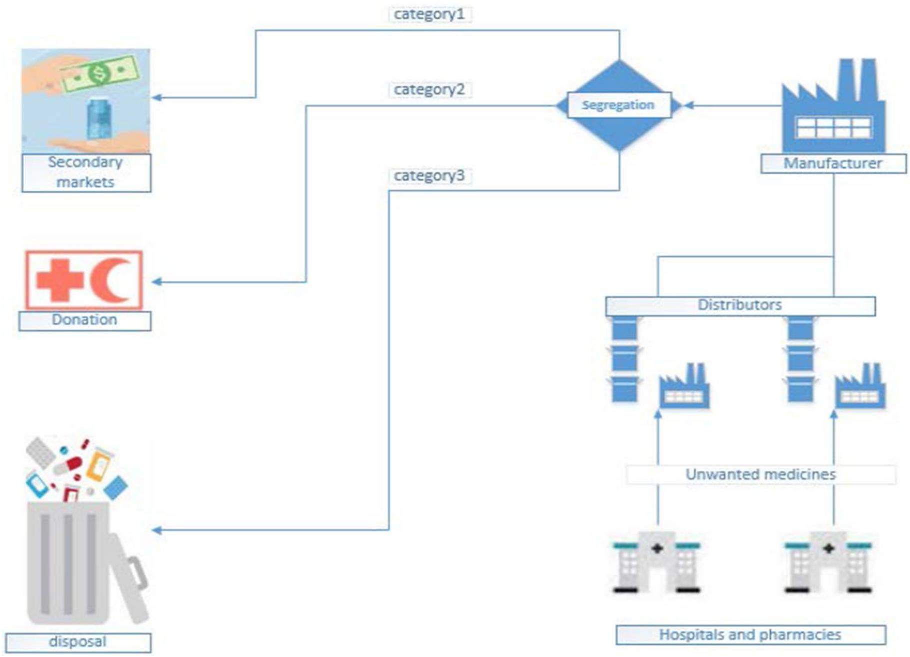


Fig. 1 Investigated reverse supply chai

the minimum amount, the government grants a subsidy. The distributors independently make an effort in corporate social responsibilities (CSR) to raise social awareness about the negative impacts of improperly disposed of medications on the environment. They also frequently visit their customers (pharmacies and hospitals) to collect unwanted drugs and transfer them to the manufacturer, similar to the work of Weraikat et al. (2016b).

In many real cases, in the pharmaceutical sector, distributors have the responsibility to visit the pharmacies to receive their orders frequently; afterward, the orders are delivered after a deterministic lead time (Nematollahi et al., 2017). The inventory system based on visit intervals is quite usual in developing countries (Chiang, 2008). Therefore, in such SCs, visit interval is one of the main factors that affect the profitability of associated members (Chiang, 2013; Nematollahi et al., 2017). The manufacturer sorts the collected medications into three categories according to their expiration date. The manufacturer can resell them in a secondary market with a lower price (category 1), which causes saving-cost, donate them to the charities (category 2), which causes tax exemption, or safety dispose of the expired ones (category 3) similar assumption as Weraikat et al. (2016b). Although the pharmaceutical reverse supply chain enhances the CSR level and thus protects the environment and public health, the manufacturer incurs extra cost. Therefore, the government grants him a subsidy for return quantities more than the minimum amount. Moreover, the manufacturer pays a grant to the distributors based on their collection level to reduce their costs. The considered sustainable pharmaceutical reverse supply chain (SPRSC) is represented in Fig. 1.

3.1 Notations

In order to model the considered SPRSC, the following notations are used in this paper.

4 Decision Variables

csr_1 Distributor 1's CSR level (decision variable).
csr_2 Distributor 2's CSR level (decision variable).

5 Parameters

G The government's penalty or subsidy rate ($/unit).
μ The government's minimum amount for collected items.
C_{seg} Segregation cost of the manufacturer ($/unit).
ρ Saving-cost of the manufacturer ($/unit).
T Tax exemption of the manufacturer ($/unit).
C_{dis} Disposal cost of each expired medications for the manufacturer ($/unit).
g The grant paid by the manufacturer to the distributors ($/unit).
b_1 The fraction of the returned medications that the manufacturer can resell in the secondary market.
b_2 The fraction of the returned medications that the manufacturer can donate to the charities.
b_3 The fraction of the returned medications that should be disposed of.
α The primary supply of returned medications.
γ Intrinsic CSR elastic coefficient.
θ Cross-CSR elastic coefficient.
ϑ Corporate social responsibility efforts cost coefficient of the distributors.
n_1 Distributor 1's visit frequency per year.
v_1 Distributor 1's visiting cost ($/unit).
ς_1 Shipping cost of per returned unwanted medication from pharmacy to manufacturer at distributor 1 ($/unit).
n_2 Distributor 2's visit frequency per year.
v_2 Distributor 2's visiting cost ($/unit).
ς_2 Shipping cost of per returned unwanted medication from pharmacy to manufacturer at distributor 2 ($/unit).
The superscripts * and ** indicate decentralized and centralized structures of each decision variable, respectively.

6 Model formulation

This paper studies a manufacturer-distributor sustainable pharmaceutical reverse supply chain (SPRSC). In order to manage the pharmaceutical waste that is hazardous to the environment and public health, the manufacturer tends to return the unwanted medications up to the government's minimum amount. The amount of medications collected by each distributor is a function of CSR levels of both distributors under competition. In other words, the CSR level of each distributor increases his returned amount and decreases his competitor's collection linearly. Thus, the return quantity of distributor 1 is $R_1(\text{csr}_1, \text{csr}_2) = \alpha + \gamma\text{csr}_1 - \theta\text{csr}_2$ and that of his competitor is $R_2(\text{csr}_1, \text{csr}_2) = \alpha + \gamma\text{csr}_2 - \theta\text{csr}_1$, in which α, γ, and θ are positive parameters. Note that similar return functions are also used by scholars, such as Hosseini-Motlagh, Nouri-Harzvili, et al. (2020). This is similar to the work of Song et al. (2017) in competitive conditions and Xie et al. (2017), who studied competitive pricing policies. In the return quantity function, α is the initial willingness of the customers to return unwanted medications, which is also known as a primary environmental awareness parameter (Zhang & Ren, 2016). Parameter γ denotes the effectiveness of each distributor's CSR participation in his customer zone, and θ is the effectiveness of each distributor's CSR participation in his competitor's customer zone. The values of γ and θ depend on some external factors including social, economic, and psychological issues. The CSR expenditure of distributor i is assumed to be a convex function taking the quadratic form $\frac{1}{2}\vartheta\text{csr}_i^2$, similar to Song et al. (2017), De Giovanni (2011), and Chernonog and Avinadav (2019). In the following, we study the decentralized, centralized, and coordinated structures.

6.1 Decentralized structure

In the decentralized structure of the sustainable pharmaceutical reverse supply chain (SPRSC), the manufacturer and the distributors minimize their costs independently. Duopolistic competing distributors individually determine the optimal levels of cooperating in socially responsible efforts affecting the return quantity of the unwanted medications, which in turn, the manufacturer's costs are influenced. In this section, the manufacturer's and distributors' cost functions are studied under the decentralized structure.

6.1.1 Manufacturer cost function

The expected cost of the reverse process of the manufacturer is as follows ($R = R_1 + R_2$):

$$C_m = C_{\text{seg}}R - b_1R\rho - b_2RT + b_3RC_{\text{dis}} - (R - \mu)G + gR = \left(2\alpha + (\gamma - \theta)(\text{csr}_1 + \text{csr}_2)\right)\left(C_{\text{seg}} + b_3C_{\text{dis}} - b_1\rho - b_2T - G + g\right) + \mu G \tag{1}$$

The first term is the segregation cost of the medications. In other words, the manufacturer checks the expiration date of the medications. If their remaining shelf life is more than one year (category 1), they can be sold in the secondary markets, which leads to saving-cost, as indicated in the second term. By experience, the manufacturer can estimate that b_1 percent of the total return quantity of the medications is in this category. If the medications have less than one-year shelf life up to a few months (category 2), the manufacturer can donate them to the charities and earn tax exemption, as indicated in the third term. By experience, b_2 percent of the total reversed medications of category 2. The rest proportion of the return quantity that is expired (category 3) should be disposed of by the manufacturer, which causes the disposal cost, as stated in the fourth term. The fifth term shows the role of the government in this supply chain (Chen & Akmalul'Ulya, 2019). If the return quantity is more than the government's minimum amount, $R > \mu$, the term is negative, and it decreases the manufacturer's costs as a subsidy. If the return quantity is less

Table 1 Changes of decentralized decision variables when model parameters increase

Parameter	Optimal decisions	
	csr_1^*	csr_2^*
$\frac{\partial N}{\partial g}$	$\frac{\gamma}{\vartheta}$	$\frac{\gamma}{\vartheta}$
$\frac{\partial N}{\partial \gamma}$	$\frac{(g-\varsigma_1)}{\vartheta}$	$\frac{(g-\varsigma_2)}{\vartheta}$
$\frac{\partial N}{\partial \vartheta}$	$\frac{(\varsigma_1-g)\gamma}{\vartheta^2}$	$\frac{(\varsigma_2-g)\gamma}{\vartheta^2}$
$\frac{\partial N}{\partial \varsigma_1}$	$-\frac{\gamma}{\vartheta}$	No Change
$\frac{\partial N}{\partial \varsigma_2}$	No Change	$-\frac{\gamma}{\vartheta}$

than the government's minimum amount, $R < \mu$, the term is positive, and it enhances the manufacturer's costs as a penalty (Chen & Akmalul'Ulya, 2019). Finally, the last term is the grant that the manufacturer pays to the distributors to help them with collecting costs.

6.1.2 Distributor's cost function

The expected cost of the reverse process of the distributors are as follows:

$$C_{D1}\left(\mathrm{csr}_1, \mathrm{csr}_2\right) = n_1 v_1 + \frac{1}{2}\vartheta \mathrm{csr}_1^2 + \varsigma_1\left(\alpha + \gamma \mathrm{csr}_1 - \theta \mathrm{csr}_2\right) - g\left(\alpha + \gamma \mathrm{csr}_1 - \theta \mathrm{csr}_2\right) \quad (2)$$

$$C_{D2}\left(\mathrm{csr}_1, \mathrm{csr}_2\right) = n_2 v_2 + \frac{1}{2}\vartheta \mathrm{csr}_2^2 + \varsigma_2\left(\alpha + \gamma \mathrm{csr}_2 - \theta \mathrm{csr}_1\right) - g\left(\alpha + \gamma \mathrm{csr}_2 - \theta \mathrm{csr}_1\right) \quad (3)$$

The first term is the cost of visiting the pharmacies or hospitals by the distributors. The second term is the CSR expenditures, as discussed before in assumptions. The third term indicates the shipping cost of collected unwanted medications from customer zone, pharmacies, and hospitals, to the manufacturer. The last term is the grant earned by the distributors.

Theorem 1 *Distributor 1's cost function is convex with respect to* csr_1.

Proof See "Appendix 1".

csr_1^* is the optimum value of distributor 1's CSR participation level, which can be calculated as follows:

$$\mathrm{csr}_1^* = \frac{\left(g - \varsigma_1\right)\gamma}{\vartheta} \quad (4)$$

Theorem 2 *Distributor 2's cost function is convex with respect to* csr_2.

Proof See "Appendix 2".

csr_2^* is the optimum value of distributor 2's CSR participation level, which minimizes the distributor 2's cost function and can be formulated as follows:

$$\mathrm{csr}_2^* = \frac{(g - \varsigma_2)\gamma}{\vartheta} \tag{5}$$

Table 1 represents first-order partial derivatives of csr_1^* and csr_2^* with respect to model parameters and illustrates the impacts of changing the parameters on the decentralized optimal decisions. We consider "N" as a dummy variable that shows optimal decisions, in Tables 1 and 2.

Table 1 reveals the following results: by increasing the distributors' grant (g), csr_1^* and csr_2^* augment by rate $\frac{\gamma}{\vartheta}$. This happens because increasing g raises their capability of participating in CSR. Increasing intrinsic CSR elastic coefficient (γ) raises csr_1^* if $g > \varsigma_1$ and increases csr_2^* if $g > \varsigma_2$. In other words, if the distributors' grants are higher than their shipping costs, by increasing γ the distributors raise their CSR efforts. Enhancing corporate social responsibility efforts cost coefficient of the distributors (ϑ) increases csr_1^* if $g < \varsigma_1$ and raises csr_2^* if $g < \varsigma_2$. Each distributor's CSR participation depends on his shipping cost under a specific decreasing rate $\left(-\frac{\gamma}{\vartheta}\right)$.

Moreover, using Eqs. (4) and (5), we can derive the decentralized returned amounts of distributors as follows:

$$R_1^*(\mathrm{csr}_1, \mathrm{csr}_2) = \alpha + \gamma^2 \frac{(g - \varsigma_1)}{\vartheta} - \theta\gamma \frac{(g - \varsigma_2)}{\vartheta} \tag{6}$$

$$R_2^*(\mathrm{csr}_1, \mathrm{csr}_2) = \alpha + \gamma^2 \frac{(g - \varsigma_2)}{\vartheta} - \theta\gamma \frac{(g - \varsigma_1)}{\vartheta} \tag{7}$$

Since the returned amounts should be positive, we have $\frac{\alpha\vartheta}{\gamma} > \left(\varsigma_1 - \theta\varsigma_2 + g(\theta - 1)\right)$ and $\frac{\alpha\vartheta}{\gamma} > \left(\varsigma_2 - \theta\varsigma_1 + g(\theta - 1)\right)$.

6.2 Centralized structure

Joint decision-making structure or centralized model considers the whole SPRSC as one entity and determines the decision variables in order to minimize the total SPRSC costs (Zabojnik, 2002) and achieve the globally optimum values of decision variables (Asl-Najafi et al., 2018). In other words, centralization neutralizes the conflict of interests between members (Jazinaninejad et al., 2019). In the investigated SPRSC, the CSR level of each distributor is determined based on the entire SPRSC point of view. Thus, in the centralized decision-making, the individual costs of members are neglected, which in turn may lead to more costs for some SPRSC members. However, the centralized model can be considered as a benchmark for measuring the SPRSC performance and determining the optimal decisions from the entire viewpoint. Under the centralized model, the SPRSC cost function is the sum of the manufacturer and the distributors' cost, which is calculated as follows:

$$\begin{aligned} C_{cen} =& C_m + C_{D1} + C_{D2} = \left(2\alpha + (\gamma - \theta)(\mathrm{csr}_1 + \mathrm{csr}_2)\right)\left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - b_1\rho - b_2 T - G\right) \\ &+ \mu G + n_1 v_1 + n_2 v_2 + \frac{1}{2}\vartheta\left(\mathrm{csr}_1^2 + \mathrm{csr}_2^2\right) + \alpha\left(\varsigma_1 + \varsigma_2\right) \\ &+ \varsigma_1\left(\gamma \mathrm{csr}_1 - \theta \mathrm{csr}_2\right) + \varsigma_2\left(\gamma \mathrm{csr}_2 - \theta \mathrm{csr}_1\right) \end{aligned} \tag{8}$$

Table 2 Changes of centralized decision variables when model parameters increase

Parameter	Optimal decisions	
	csr_1^{**}	csr_2^{**}
$\frac{\partial N}{\partial C_{seg}}$	$\frac{(\theta-\gamma)}{\vartheta}$	$\frac{(\theta-\gamma)}{\vartheta}$
$\frac{\partial N}{\partial \gamma}$	$\frac{-X-\varsigma_1}{\vartheta}$	$\frac{-X-\varsigma_2}{\vartheta}$
$\frac{\partial N}{\partial \theta}$	$\frac{X+\varsigma_2}{\vartheta}$	$\frac{X+\varsigma_1}{\vartheta}$
$\frac{\partial N}{\partial \vartheta}$	$\frac{(\gamma-\theta)X+\gamma\varsigma_1-\varsigma_2\theta}{\vartheta^2}$	$\frac{(\gamma-\theta)X+\gamma\varsigma_2-\varsigma_1\theta}{\vartheta^2}$
$\frac{\partial N}{\partial \varsigma_1}$	$-\frac{\gamma}{\vartheta}$	$\frac{\theta}{\vartheta}$
$\frac{\partial N}{\partial \varsigma_2}$	$\frac{\theta}{\vartheta}$	$-\frac{\gamma}{\vartheta}$
$\frac{\partial N}{\partial b_1}$	$\frac{(\gamma-\theta)\rho}{\vartheta}$	$\frac{(\gamma-\theta)\rho}{\vartheta}$
$\frac{\partial N}{\partial b_2}$	$\frac{(\gamma-\theta)T}{\vartheta}$	$\frac{(\gamma-\theta)T}{\vartheta}$
$\frac{\partial N}{\partial b_3}$	$\frac{(\theta-\gamma)C_{dis}}{\vartheta}$	$\frac{(\theta-\gamma)C_{dis}}{\vartheta}$
$\frac{\partial N}{\partial C_{dis}}$	$\frac{(\theta-\gamma)b_3}{\vartheta}$	$\frac{(\theta-\gamma)b_3}{\vartheta}$
$\frac{\partial N}{\partial \rho}$	$\frac{(\gamma-\theta)b_1}{\vartheta}$	$\frac{(\gamma-\theta)b_1}{\vartheta}$
$\frac{\partial N}{\partial T}$	$\frac{(\gamma-\theta)b_2}{\vartheta}$	$\frac{(\gamma-\theta)b_2}{\vartheta}$
$\frac{\partial N}{\partial G}$	$\frac{(\gamma-\theta)}{\vartheta}$	$\frac{(\gamma-\theta)}{\vartheta}$

Theorem 3 *The sustainable pharmaceutical reverse supply chain cost function is convex with respect to* csr_1 *and* csr_2.

Proof See "Appendix 3".

The optimum values of $\mathrm{csr}_1$and csr_2, that minimize the SPRSC cost, can be calculated as follows:

$$\mathrm{csr}_1^{**} = \frac{(\theta-\gamma)\left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - b_1\rho - b_2 T - G\right) - \gamma\varsigma_1 + \varsigma_2\theta}{\vartheta} \tag{9}$$

$$\mathrm{csr}_2^{**} = \frac{(\theta-\gamma)\left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - b_1\rho - b_2 T - G\right) - \gamma\varsigma_2 + \varsigma_1\theta}{\vartheta} \tag{10}$$

Here we investigate the changing rate of centralized decisions when model parameters change. Table 2 indicates the first-order derivative of csr_1^{**} and csr_2^{**} with respect to the parameters in the model. Note that $X = \left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - b_1\rho - b_2 T - G\right)$.

Table 2 reveals the following results: although distributors' grant affects their CSR level under the decentralized system (see Table 1), g is eliminated under the centralized model because the distributors make decisions from the perspective of the entire chain. On the other hand, increasing the government's penalty or subsidy rate (G), tax exemption of the manufacturer (T), saving-cost of the manufacturer (ρ), b_2, and b_1 increase the distributors' CSR participation, while these parameters do not affect the decentralized optimal decisions (see Table 1). Note that it is rational for θ to be less than γ. Augmenting the manufacturer's segregation cost (C_{seg}), disposing cost (C_{dis}), and b_3 reduce the distributors' centralized CSR efforts. Though, none of these parameters influence CSR practices under the decentralized structure (see Table 1). Increasing each distributor's shipping cost under the centralized system not only affects his own CSR participation level by decreasing rate $(-\frac{\gamma}{\vartheta})$ but also raises his competitor's CSR efforts by the rate $(\frac{\theta}{\vartheta})$.

If X is negative, the following results are concluded: raising the cross-CSR elastic coefficient (θ) and corporate social responsibility efforts cost coefficient of the distributors (ϑ) decrease the optimal CSR participation of the distributors under the centralized system. However, augmenting intrinsic CSR elastic coefficient (γ) increases the centralized optimal decisions, since the distributors' CSR efforts have a higher effect on their return quantity and they are encouraged to participate more in CSR activities.

On the other hand, if X is positive, raising cross-CSR elastic coefficient (θ) increases the centralized optimal decisions; augmenting corporate social responsibility efforts cost coefficient of the distributors (ϑ) increases distributor 1's CSR efforts if $(\gamma - \theta)X + \gamma\varsigma_1 > \varsigma_2\theta$, and increases distributor 2's CSR efforts if $(\gamma - \theta)X + \gamma\varsigma_2 > \varsigma_1\theta$; moreover, raising the intrinsic CSR elastic coefficient (γ) reduces the centralized CSR activities. Moreover, using Eqs. (9) and (10), we can derive the centralized returned amounts of distributors as follows:

$$R_1^{**}\left(\mathrm{csr}_1, \mathrm{csr}_2\right) = \alpha + \frac{1}{\vartheta}((\theta-\gamma)^2\left(G - C_{\mathrm{seg}} - b_3C_{\mathrm{dis}} + b_1\rho + b_2T\right) - \left(\gamma^2+\theta^2\right)\varsigma_1 + 2\theta\gamma\varsigma_2 - \left(\gamma^2+\theta^2\right)\varsigma_1 + 2\theta\gamma\varsigma_2)) \tag{11}$$

$$R_2^{**}\left(\mathrm{csr}_1, \mathrm{csr}_2\right) = \alpha + \frac{1}{\vartheta}((\theta-\gamma)^2\left(G - C_{\mathrm{seg}} - b_3C_{\mathrm{dis}} + b_1\rho + b_2T\right) - \left(\gamma^2+\theta^2\right)\varsigma_2 + 2\theta\gamma\varsigma_1) - \left(\gamma^2+\theta^2\right)\varsigma_2 + 2\theta\gamma\varsigma_1) - \left(\gamma^2+\theta^2\right)\varsigma_2 + 2\theta\gamma\varsigma_1) \tag{12}$$

Since the returned amounts should be positive, we have $\alpha\vartheta + (\theta-\gamma)^2\left(G - C_{\mathrm{seg}} - b_3C_{\mathrm{dis}} + b_1\rho + b_2T\right) + 2\theta\gamma\varsigma_2 > \left(\gamma^2+\theta^2\right)\varsigma_1$ and $\alpha\vartheta + (\theta-\gamma)^2\left(G - C_{\mathrm{seg}} - b_3C_{\mathrm{dis}} + b_1\rho + b_2T\right) + 2\theta\gamma\varsigma_1 > \left(\gamma^2+\theta^2\right)\varsigma_2$.

6.3 Coordination mechanism

Although the centralized decision-making structure minimizes the total supply chain cost, it may enhance the expenditures of some members (Lu et al., 2017). In this case, centralization leads to an increase in the distributors' CSR level to avoid governmental penalties by increasing the return quantity. Therefore, the distributors' costs enhance in comparison with the decentralized ones. Accordingly, the manufacturer proposes an incentive mechanism to encourage the distributors to participate in a joint decision-making structure. In other words, the manufacturer persuade them to make decisions based on the centralized values of the decision variables, $\mathrm{csr}_1^{**}$and csr_2^{**}. The purpose of implementing the coordination model is to decline the SPRSC costs, besides the deduction of each member's cost. There are many coordination contracts in the literature of channel coordination (Chen et al., 2012). In this study, however, a customized coordination contract is developed based on the investigated case. More precisely, the manufacturer devises a novel saving-cost sharing contract, due to which λ_1 and λ_2 percent of the saving-cost contribute to the distributors 1 and 2 respectively, so that the costs of all SPRSC members decrease. Note that the manufacturer's saving-cost is the profit that he gains via reselling the returned medications of category 1 and donating those of category 2, which leads to tax exemption. As a result, both distributors participate in the proposed contract.

The manufacturer and the distributors cost functions under the proposed coordination contract, due to the former explanations, would be as follows (Note that the superscript "coo" on each function denotes the coordinated structure.):

$$\begin{aligned} C_m^{\mathrm{coo}} =& C_{\mathrm{seg}}R - \left(1 - \lambda_1 - \lambda_2\right)b_1 R\rho - b_2 RT + b_3 RC_{\mathrm{dis}} - (R-\mu)G + gR \\ &= \left(2\alpha + (\gamma - \theta)\left(\mathrm{csr}_1 + \mathrm{csr}_2\right)\right)\left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - \left(1 - \lambda_1 - \lambda_2\right)b_1\rho - b_2 T - G + \mu + g\right) \end{aligned} \tag{13}$$

$$\begin{aligned} C_{D1}^{\mathrm{coo}}(\mathrm{csr1},\mathrm{csr2}) &= n_1 v_1 + \frac{1}{2}\vartheta \mathrm{csr}_1^2 + (\varsigma_1 - g)R_1 - \lambda_1 b_1 R\rho \\ &= n_1 v_1 + \frac{1}{2}\vartheta \mathrm{csr}_1^2 + (\varsigma_1 - g)\left(\alpha + \gamma \mathrm{csr}_1 - \theta \mathrm{csr}_2\right) \\ &= n_1 v_1 + \frac{1}{2}\vartheta \mathrm{csr}_1^2 + (\varsigma_1 - g)\left(\alpha + \gamma \mathrm{csr}_1 - \theta \mathrm{csr}_2\right) \\ &\quad - \lambda_1 b_1 \rho\left(2\alpha + (\gamma - \theta)\left(\mathrm{csr}_1 + \mathrm{csr}_2\right)\right) \end{aligned} \tag{14}$$

$$\begin{aligned} C_{D2}^{\mathrm{coo}}(\mathrm{csr1},\mathrm{csr2}) &= n_2 v_2 + \frac{1}{2}\vartheta \mathrm{csr}_2^2 + (\varsigma_2 - g)R_2 - \lambda_2 b_1 R\rho \\ &= n_2 v_2 + \frac{1}{2}\vartheta \mathrm{csr}_2^2 + +(\varsigma_2 - g)\left(\alpha + \gamma \mathrm{csr}_2 - \theta \mathrm{csr}_1\right) \\ &\quad - \lambda_2 b_1 \rho\left(2\alpha + (\gamma - \theta)\left(\mathrm{csr}_1 + \mathrm{csr}_2\right)\right) \end{aligned} \tag{15}$$

The saving-cost sharing factors, λ_1 and λ_2, take values between zero and 1, and they must be determined carefully so that the contract reduces the cost of all SPRSC members in comparison to the decentralized structure. To calculate the maximum values of λ_1 and λ_2, we consider that the cost of the manufacturer in the coordinated model should be less than his cost in the decentralized structure. In other words, $C_m^{\mathrm{coo}} \le C_m^{\mathrm{dec}}$. If we define $\lambda = \lambda_1 + \lambda_2$, the total saving-cost sharing factor, the upper bond of λ, $\lambda^{\max}$, would be as follows:

$$\lambda \le \frac{A}{b_1\rho\left(2\alpha + (\gamma - \theta)\left(\mathrm{csr}_1^{**} + \mathrm{csr}_2^{**}\right)\right)} = \lambda^{\max} \tag{16}$$

where

$$A = \left((\gamma - \theta)\left(\left(\mathrm{csr}_1^{*} + \mathrm{csr}_2^{*}\right) - \left(\mathrm{csr}_1^{**} + \mathrm{csr}_2^{**}\right)\right)\right)\left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - b_1\rho - b_2 T - G + g\right) + \mu G \tag{17}$$

If the manufacturer's cost in the coordinated structure is more than the decentralized one, $\lambda > \lambda^{\max}$, the manufacturer does not accept the coordination contract. On the other hand, to satisfy distributors to participate in the coordinated scheme, the cost of them in the coordinated structure should be less than the decentralized one, $C_{D1}^{\mathrm{coo}} \le C_{D1}^{\mathrm{dec}}$. Otherwise, the distributors would not accept the coordination contract since shifting to the centralized structure raises their expenditures. Hence, the minimum saving-cost sharing factor, $\lambda_1^{\min}$, that satisfies the distributor 1 to decide based on the centralized model is as follows:

$$\lambda_1^{\min} = \frac{\frac{1}{2}\vartheta\left(\mathrm{csr}_1^{2**} - \mathrm{csr}_1^{2*}\right) + \left(\varsigma_1 - g\right)\left(\left(\gamma \mathrm{csr}_1^{**} - \theta \mathrm{csr}_2^{**}\right) - \left(\gamma \mathrm{csr}_1^{*} - \theta \mathrm{csr}_2^{*}\right)\right)}{b_1\rho\left(2\alpha + (\gamma - \theta)\left(\mathrm{csr}_1^{**} + \mathrm{csr}_2^{**}\right)\right)} \tag{18}$$

If $\lambda_1 < \lambda_1^{\min}$, the cost of distributor 1 in the coordinated model is more than its cost under the decentralized structure; therefore, the coordination is not achievable. In a similar methodology, we can calculate the minimum value of the saving-cost sharing factor from distributor 2's point of view as follows:

$$\lambda_2^{\min} = \frac{\frac{1}{2}\vartheta\left(\mathrm{csr}_2^{2^{**}} - \mathrm{csr}_2^{2^{*}}\right) + \left(\varsigma_2 - g\right)\left(\left(\gamma \mathrm{csr}_2^{**} - \theta \mathrm{csr}_1^{**}\right) - \left(\gamma \mathrm{csr}_2^{*} - \theta \mathrm{csr}_1^{*}\right)\right)}{b_1\rho\left(2\alpha + (\gamma - \theta)\left(\mathrm{csr}_1^{**} + \mathrm{csr}_2^{**}\right)\right)} \quad (19)$$

It can be derived that if $\lambda > \lambda^{\max}$, the distributors earn all benefits. In addition, if $\lambda_1 = \lambda_1^{\min}$, the cost of distributor 1 in the coordinated model is equal to his costs in the decentralized model. Also, if $\lambda_1 = \lambda_1^{\min}$ and $\lambda_2 = \lambda_2^{\min}$, the coordination contract reduces the manufacturer's cost, but the cost of each distributor remains as same as the decentralized one. To achieve the optimal values of λ_1 and λ_2, similar to the work of Chaharsooghi and Heydari (2010), the bargaining strategy is used to distribute the saving-cost between the SPRSC members fairly. In this method, first, we calculate the total SPRSC costs under centralization. Then, the amount of SPRSC cost reduced by shifting to the centralized decision-making, reduced cost of SPRSC, can be calculated as follow ($\Delta C_{\mathrm{RSC}} > 0$):

$$\Delta C_{\mathrm{RSC}} = C_{\mathrm{RSC}}^{\mathrm{dec}} - C_{\mathrm{RSC}}^{\mathrm{cen}} \quad (20)$$

In Eq. 20, $C_{\mathrm{RSC}}^{\mathrm{dec}}$ is the total SPRSC costs (summation of the manufacturer and the distributors' costs) for the optimum values of the decision variables under the decentralized decision-making structure. Similarly, $C_{\mathrm{RSC}}^{\mathrm{cen}}$ is the total SPRSC costs for the optimum values of the decision variables under the centralized decision-making structure.

$$\begin{aligned}\Delta C_{\mathrm{RSC}} = {} & \left((\gamma - \theta)\left(\left(\mathrm{csr}_1^{*} + \mathrm{csr}_2^{*}\right) - \left(\mathrm{csr}_1^{**} + \mathrm{csr}_2^{**}\right)\right)\right)\left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - b_1\rho - b_2 T - G\right) \\ & + \frac{1}{2}\vartheta\left(\left(\mathrm{csr}_1^{2*} + \mathrm{csr}_2^{2*}\right) - \left(\mathrm{csr}_1^{2**} + \mathrm{csr}_2^{2**}\right)\right) + \varsigma_1\left(\left(\gamma \mathrm{csr}_1^{*} - \theta \mathrm{csr}_2^{*}\right) - \left(\gamma \mathrm{csr}_1^{**} - \theta \mathrm{csr}_2^{**}\right)\right) \\ & + \varsigma_2\left(\left(\gamma \mathrm{csr}_2^{*} - \theta \mathrm{csr}_1^{*}\right) - \left(\gamma \mathrm{csr}_2^{**} - \theta \mathrm{csr}_1^{**}\right)\right)\end{aligned} \quad (21)$$

Finally, this amount of saving-cost earned by the manufacturer should be fairly distributed between all members according to their saving-cost sharing factors, λ_1 and λ_2. Therefore, the optimum values of λ_1 and λ_2 are calculated as follows:

$$C_{D1}^{\mathrm{coo}} = C_{D1}^{\mathrm{dec}} - \lambda_1 \Delta C_{\mathrm{RSC}} \quad (22)$$

$$\lambda_1 = \frac{\frac{1}{2}\vartheta\left(\mathrm{csr}_1^{2*} - \mathrm{csr}_1^{2**}\right) + \left(\varsigma_1 - g\right)\left(\left(\gamma \mathrm{csr}_1^{*} - \theta \mathrm{csr}_2^{*}\right) - \left(\gamma \mathrm{csr}_1^{**} - \theta \mathrm{csr}_2^{**}\right)\right)}{\left[\Delta C_{\mathrm{RSC}} - b_1\rho\left(2\alpha + (\gamma - \theta)\left(\left(\mathrm{csr}_1^{**} + \mathrm{csr}_2^{**}\right) - \left(\mathrm{csr}_1^{*} + \mathrm{csr}_2^{*}\right)\right)\right)\right]} \quad (23)$$

$$C_{D2}^{coo} = C_{D2}^{dec} - \lambda_2 \Delta C_{RSC} \quad (24)$$

$$\lambda_2 = \frac{\frac{1}{2}\vartheta\left(csr_2^{2*} - csr_2^{2**}\right) + \left(\varsigma_2 - g\right)\left(\left(\gamma csr_2^{*} - \theta csr_1^{*}\right) - \left(\gamma csr_2^{**} - \theta csr_1^{**}\right)\right)}{\left[\Delta C_{RSC} - b_1\rho\left(2\alpha + (\gamma - \theta)\left(\left(csr_2^{**} + csr_1^{**}\right) - \left(csr_2^{*} + csr_1^{*}\right)\right)\right)\right]} \quad (25)$$

By implementing the coordination mechanism, λ_1 and λ_2 percent of saving- cost belongs to distributors 1 and 2, respectively.

Table 3 The results of running the model

Parameters	Decentralized structure	Centralized structure	Coordinated structure
csr_1	0.84	3.95	3.95
csr_2	0.7	3.7	3.7
R_1	72.03	77.3	77.3
R_2	70.28	74.17	74.17
R	142.31	151.47	151.47
C_m	181.9	126	178.58
C_{D1}	27.27	44.31	14.8
C_{D2}	28.04	43.56	20.49
C_{RSC}	237.22	213.88	213.88

Table 4 The coordination parameters

Parameter	Optimum	Bounds	Results
λ_1	0.1	$\lambda_1^{\min}$	0.05
λ_2	0.08	λ_2^{min}	0.05
λ	0.19	λ^{max}	0.2

7 Case study

This study is motivated by the issue of pharmaceutical waste management in SABZ DARU Company, an antibiotics manufacturer located in Tehran province where his duopolistic competing distributors tend to participate in CSR activities because of the governmental environmental legislation. Due to this legislation, the minimum returned amount of the manufacturer is $\mu = 150$ units per year, and the penalty/subsidy for deficit/excess is $G = \$7$ per unit. Hence, the SPRSC members adopt a program for the customers to collect the unwanted antibiotics of all customers and protect the environment. In this program, the distributors aim to increase the social awareness about the negative impacts of improperly disposed of antibiotics on the environment through corporate social responsibilities (CSR) efforts. These efforts not only enhance the collection level of the unwanted antibiotics but also decrease the proportion of expired ones among collected items and therefore decrease the manufacturer's costs. The segmentation cost of the manufacturer is$C_{\text{seg}} = \$2$ per unit. Then, the antibiotics are sorted into 3 categories, based on their shelf life. Category 1 includes the antibiotics with shelf life more than 1 year, category 2 contains antibiotics with remaining shelf life more than 6 months, and category 3 includes antibiotics with shelf life less than 6 months. The distributors' visit frequencies are $n_1 = 8$ and $n_2 = 9$ times per year at the cost $v_1 = \$6$ per visit and $v_2 = \$5$ per visit, respectively. The proportion of antibiotics that can be resold at the price $\rho = \$4$ per unit in the secondary market, related to category 1, is $b_1 = 0.45$. Also, $b_2 = 0.5$ is the fraction of returned quantity that can be dedicated to charities, which results in tax exemption $T = \$5$ per unit. The rest of the collected amount should be disposed of safely with the unit cost $C_{dis} = \$20$. In addition, the manufacturer pays a grant $g = \$2.2$ per unit to the distributors to help them reduce their collection costs. The initial supply of unwanted antibiotics is $\alpha = 70$ units per year. The effects of CSR on the returned quantity, intrinsic and cross-CSR elastic coefficients

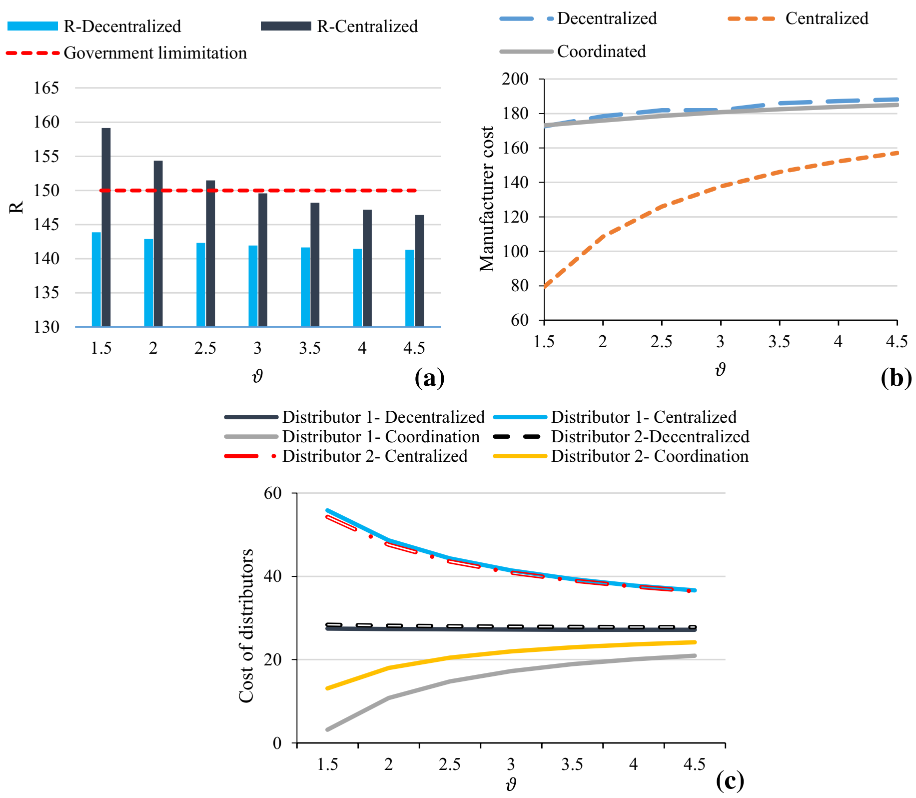


Fig. 2 The changes in the model by increasing ϑ

are $\gamma = 7$ and $\theta = 5.5$, respectively. Also, the corporate social responsibility efforts cost coefficient of the distributors is $\vartheta = \$2.5$ per level CSR. Finally, $\varsigma_1 = \$1.9$ per unit and $\varsigma_2 = \$1.95$ per unit are the shipment costs of distributor 1 and distributor 2 for transferring their returned items to the manufacturer, respectively.

Results of running the investigated model under the decentralized, centralized, and coordinated decision-making structures are indicated in Table 3. Table 3 reveals the following results: (a) from the economic point of view, by shifting from the decentralized to centralized/coordinated structure, the total costs of the SPRSC reduce from 237.22 to 213.88; (b) from the social perspective, the CSR levels of the distributors (csr_1, csr_2) enhance from (0.84, 0.7) under the decentralized structure to (3.95, 3.7) under the centralized/coordinated one; (c) from the environmental viewpoint, the returned quantities (R_1, R_2) increase from (72.03, 70.28) to (77.3, 74.17). Accordingly, three aspects of sustainability are remarkably improved by implementing the proposed saving-cost sharing contract. On the other hand, the distributors' costs (C_{D1}, C_{D2}) increase from (27.27, 28.04) under the decentralized model to (44.31, 43.56) under the centralized model, and thus they do not participate in the centralized structure, which shows the importance of an appropriate coordination contract. The manufacturer shares the saving-cost between the distributors due to their sharing cost factors (λ_1, λ_2). According to the results of Table 4, the optimum values of λ_1 and λ_2 are more than their lower bounds, which are

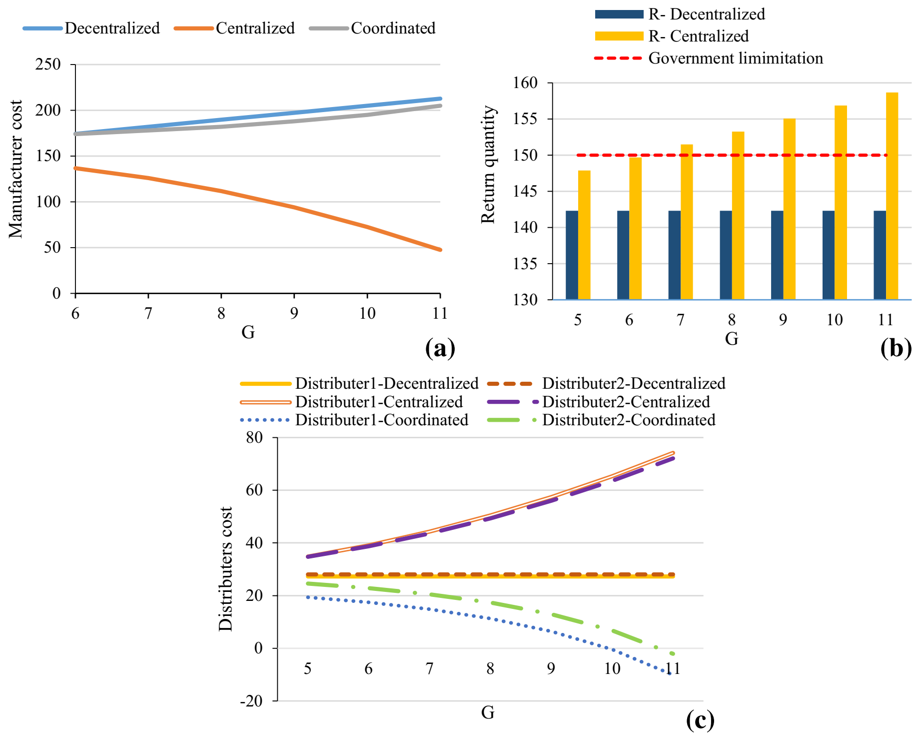


Fig. 3 The changes in the model by increasing G

determined by the distributors. These lower bounds are the minimum acceptable saving-cost sharing factors that guarantee the distributors' participation in the coordination model. In this case, the costs of distributors 1 and 2 are 14.8 and 20.49, respectively. Also, $\lambda_1 + \lambda_2$ does not exceed the upper bound of λ, which is the maximum allowable saving-cost sharing from the manufacturer viewpoint. Accordingly, the proposed coordination scheme is applicable. Any amount of λ beyond λ^{max} is not acceptable for the manufacturer. By implementing the coordination mechanism, the costs of all SPRSC members decrease. Therefore, the distributors shift their decision variables to centralized optimum values. These changes augment the CSR levels and returned quantities of the distributors, which serve the aim of improving the sustainability level through protecting the environment and public health.

8 Sensitivity analyses

In this section, a set of sensitivity analyses are proposed to evaluate the parameters' interactions and their effects on the model. The impact of corporate social responsibility efforts cost coefficient of the distributors (ϑ) on the manufacturer's cost, distributors' costs, and the total collected amount is investigated in Fig. 2. We can see that as ϑ increases, the manufacturer's cost increases in all decision-making models (see Fig. 2b) because an increase in ϑ decreases the returned quantity (see Fig. 2a), which in turn enhances the manufacture's

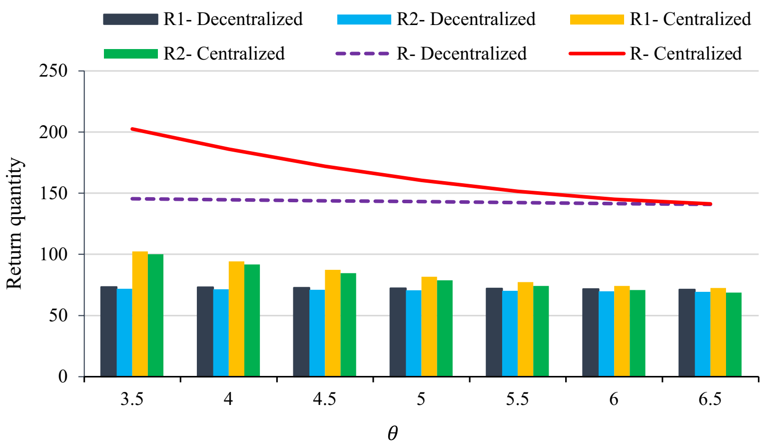


Fig. 4 The changes in the distributors' return quantity by increasing θ

penalty. Also, by increasing the CSR cost coefficient (ϑ) the CSR levels of the distributors reduce gradually. In such a case, the return quantity reduces in all decision-making structures, which is not pleasant from the environmentally friendly point of view (see Fig. 2a). Moreover, due to the legislation, the manufacturer's costs increase (see Fig. 2b) because he incurs a penalty for $\vartheta \geq 3$ (see Fig. 2a). While, for $\vartheta \leq 2.5$, since the returned quantity is beyond the government's minimum amount (see Fig. 2a), the manufacturer earns subsidy, and his costs reduce. It is noteworthy that in the coordinated/centralized model, the returned quantities of both distributors are much higher than those of the decentralized one for any values of ϑ (see Fig. 2a). As a result, participation in coordination leads to augmentation in CSR levels and prevents environmental degradation. Additionally, for lower values of distributors' corporate social responsibility efforts cost coefficient (ϑ), the cost reduction of distributors is more than the higher ones (see Fig. 2c. As Fig. 2c shows, for any values of ϑ, the coordinated system is capable of reducing the distributors' costs. Increasing ϑ in the coordinated model augments the distributors' costs, which is on the contrary of the centralized structure.

According to Fig. 3b, the returned quantity of the reverse supply chain in the centralized model is growing up to more than the regulatory minimum amount by increasing the government's penalty/subsidy rate (G). Therefore, as shown in Fig. 3a, the augmentation of G reduces the manufacturer's centralized costs since he gains subsidy. The return quantity passes the regulatory minimum amount for $G \geq 7$, which causes an acceleration in cost reduction, due to the government subsidy for the manufacturer (see Fig. 3b). On the other hand, under the decentralized model, the total return quantity is less than the regulatory minimum amount, and as G increases, the manufacturer's costs grow due to the governmental penalty on returned quantity shortage (see Fig. 3a). In other words, increasing G raises the manufacturer's claims for more return quantity and CSR levels. As Fig. 3c shows, due to the independence of the SPRSC members' decision-making under the decentralized model, the distributors will not increase their CSR levels, and they make their decisions individually. However, in the centralized decision-making structure, increasing G augments the CSR level and return quantity of the distributors to avoid governmental penalties and potential detrimental impacts of pharmaceutical leftovers on the environment. In this case,

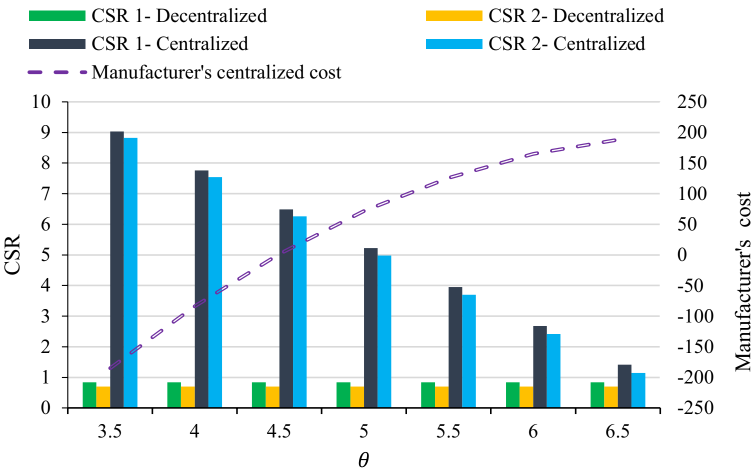


Fig. 5 The changes in the distributors' level of CSR efforts and manufacturer's costs by increasing θ

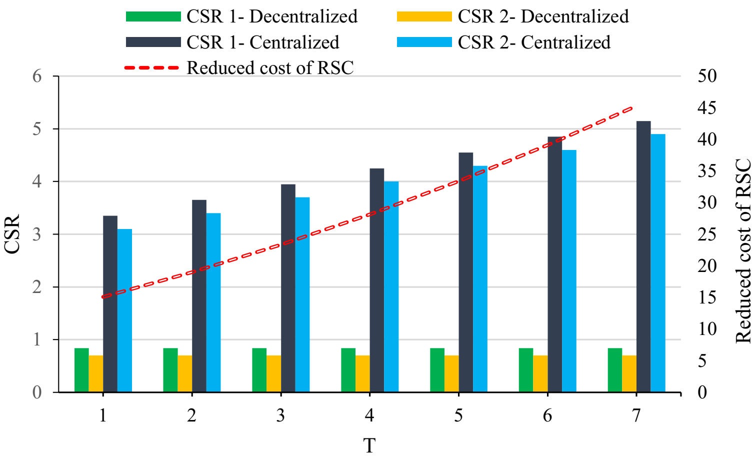
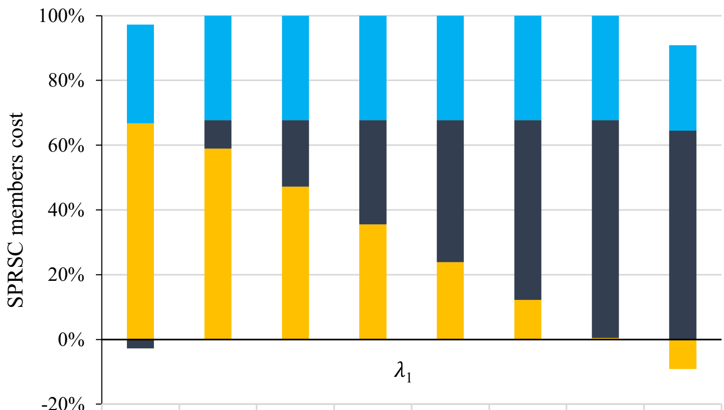


Fig. 6 The changes in the distributors' level of CSR efforts and reduced cost of SPRSC by increasing T

the distributors' costs increase, and they will not participate in centralization (see Fig. 3c). Thus, this is where the necessity of the coordination mechanism rises up.

Figure 4 depicts the changes in the returned quantity of the distributors by changing the cross-CSR effect (θ). Note that the cross-CSR effect represents the influences of the distributors' CSR efforts on one another's performance. The returned quantity in the coordinated/centralized structure is greater than that of the decentralized one for any rational values of θ, which indicates the applicability of the proposed saving-cost sharing contract. However, increasing θ, declines the difference between R^{dec} and R^{coo}. Moreover, as θ grows, the total returned quantity and the returned quantity of each distributor decrease.

Figure 5 shows the impacts of changing the cross-CSR effect (θ) on the level of CSR participation of the distributors. Augmentation of θ reduces the CSR level of the distributors in the centralized structure since their competition weakens the level of each



	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13
Distributor 2	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Distributor 1	-0.03	0.09	0.20	0.32	0.44	0.55	0.67	0.79
Manufacturer	0.71	0.59	0.47	0.36	0.24	0.12	0.00	-0.11

Fig. 7 The changes in the proportion of the reduced cost earned by RSC members by changing λ_1 for $\lambda_2 = 0.08$

distributor's CSR efforts. From the manufacturer's point of view, if the distributors participate less in CSR, his costs increase due to the reduction of returned quantity. In such a case, the environment faces a higher risk due to unmanaged pharmaceutical waste. As θ lessens in the centralized/coordinated model, not only do the distributors participate more in CSR efforts, but the manufacturer's costs also reduce due to the augmentation of collected unwanted antibiotics. Even for $\theta \leq 3.5$, the manufacturer gains profit from the reverse supply chain in the centralized model.

Tax exemption of the manufacturer, T per unit, as a reward of his donation, affects the distributors' CSR level in some ways. As shown in Fig. 6, raising tax exemption increases the amount of saving-cost of the SPRSC, which is the reduced cost obtained by the centralized structure in comparison to the decentralized one. Therefore, each distributor's share of saving-cost rises, as well. As a result, they are encouraged to participate more in CSR efforts, which enhances their return quantity and protects the earth from leftover antibiotics. The more the returned quantity, the more proportion of the return is donated to charities, and thus, the more tax exemption the manufacturer earns. Also, this raises the saving-cost and share of the distributors.

In a coordination mechanism, it is of high importance to fairly divide the saving-cost among RSC members. The effects of saving-cost sharing factors on the RSC cost division in the coordination mechanism are shown in Figs. 7 and 8. For different values of λ_1 and λ_2, the earned proportion of saving-cost of each RSC member changes. In Fig. 7, the fraction of the saving-cost that belongs to the distributor 2 is constant since λ_2 is constant. Also, the value of λ_1 changes within its feasible range. As λ_1 increases, the proportion of the reduced cost of RSC, ΔC_{RSC}, which is shared with the distributor 1 raises, and the remained benefit for the manufacturer reduces. The lower bound of λ_1 is equal to 0.06 and the upper bound of $\lambda_1 + \lambda_2$ is equal to 0.2 (see Table 4). If these constraints are not satisfied, the RSC coordination cannot be achieved. According to Fig. 8, the distributor 1's share of the reduced cost of RSC is negative under $\lambda_1 = 0.06$. Also, the manufacturer's share of ΔC_{RSC} is negative under $\lambda_1 = 0.13$. Thus, RSC coordination cannot be achieved under these two conditions. For $\lambda_1 = 0.1$, 44 percent of the reduced cost of RSC is shared with distributor 1, 32 percent is shared with distributor 2, and the manufacturer keeps the rest 24 percent for himself. Similarly, for $\lambda_1 = 0.07$, distributor 1 earns 9 percent of the ΔC_{RSC}, distributor 2 earns 32 percent, and the manufacturer's proportion is zero.

8.1 Managerial insights

In what follows, the major managerial implications are presented.

- Managers of pharmaceutical companies can gain monetary benefits from the saving-cost sharing mechanism by reducing their costs and governmental penalties.
- Also, companies can present a positive social image of their companies, thereby increasing the collected amount of unwanted medications and moving toward sustainability, for any rational values of ϑ and government's penalty/subsidy rate (G) (see Fig. 3).
- The proposed model reduces the costs of individual members, which guarantees that they cooperate toward the mutually defined aim of achieving the perfect performance of the chain and protecting public health and environment.
- The distributors' costs remarkably reduce by implementing the proposed saving-cost sharing contract, especially for lower values of distributors' corporate social responsibility efforts cost coefficient (ϑ) (see Fig. 2).
- Managers of pharmaceutical companies can enjoy from the proposed model, especially when the cross-CSR effect (θ) is low since the gap between the decentralized and coordinated collected amount is considerable. In such a case, the saving-cost sharing scheme remarkably lessens the pharmaceutical manufacturer's costs and increases the distributors' CSR efforts (see Figs. 4 and 5).

9 Conclusion

Increasing the negative impacts of improperly discarded medications on human and environmental health has raised international awareness of the high significance of sustainability in the pharmaceutical industry. In fact, governmental regulations and customers' expectations force companies to participate in sustainability activities and reduce the amount of pharmaceutical leftovers in the environment. To the best of our knowledge, this study is the first to examine the role of competitive CSR participation of pharma-distributors via increasing social awareness about returning unwanted medications. We investigate a two-level sustainable pharmaceutical reverse supply chain (SPRSC) of antibiotics, consisting of duopolistic competing distributors and a manufacturer who faces governmental environmental obligations and has to collect a minimum amount of unwanted medications from customers. The distributors collect unwanted medications from customer zones and participate in corporate social responsibilities. The effects of distributors' CSR participation on the return quantity and costs of SPRSC members are investigated under competition. A real case study of an antibiotic manufacturer is investigated under the decentralized, centralized, and coordinated decision-making structures. In the investigated SPRSC, by shifting from the decentralized to centralized structure, the total costs of the SPRSC reduce, the CSR levels of the distributors enhance, and the returned quantity increases, as well. Although these changes are desirable from the social and environmental viewpoint, the distributors incur more costs under the centralized model compared to the decentralized one, and therefore, they refuse to take part in the centralized structure. Thus, we propose an incentive mechanism named saving-cost sharing contract to convince the distributors to participate in the coordination model. The proposed coordinated model provides suitable cost-sharing factors as incentives, which satisfy all members' participation and also balance the costs and social responsibility levels of the distributors. Under the coordination contract, the manufacturer shares the saving-cost of SPRSC between the distributors according to their sharing cost factors. This model not only reduces the SPRSC costs and the costs of individual members but also enhances the CSR level of the SPRSC and meets the aim of protecting public health and the environment.

It can be inferred from the sensitivity analysis that the manufacturer and the distributors' costs are reduced by shifting from the decentralized model to the coordinated one. For lower values of distributors' corporate social responsibility efforts cost coefficient (ϑ), the cost reduction of distributors is more than the higher ones (see Fig. 2). Additionally, the returned quantity of the SPRSC is improved by shifting from the decentralized model to the coordinated one for every value of ϑ and government's penalty/subsidy rate (G) (see Fig. 3). Also, the gap between the returned quantity under the decentralized and the coordinated model is highlighted in lower values of the cross-CSR effect (θ), which lessens the manufacturer's costs and increases the distributors' CSR efforts extremely (see Figs. 4 and 5).

Like other works, the current study is not without limitation and can be extended in several directions. For instance, in this study, we assumed that the visiting frequency of competing distributors is fixed. However, in practice, the distributors may be able to determine their visiting frequencies. Extending this study by considering the visiting frequency as a decision variable is interesting. Likewise, we considered that the distributors collect unwanted medications, while in some real-world situations, companies lack the facilities and equipment for the collection process. And thus, third party logistics providers assume the collection responsibility. Accordingly, this study can be developes by considering the impact of third party collectors in collecting and disposing of unwanted medications. Moreover, in this paper, we proposed a new saving-cost sharing contract to coordinate the channel, though it may not be practical to supply chains with different structures. As a future study, one could apply other coordination contracts for coordinating the investigated SPRSC. In addition, it is assumed that the distributor's CSR investment cost is known to all supply chain actors. However, in practice, the distributor usually has private information about CSR effort investment cost, which may not be known to the manufacturer. Therefore, this model can be extended in asymmetric CSR investment information. A side from these issues, due to effect of government's penalty/subsidy rate and minimum amount of collected medicines on sustainability pillars in this model, we suggest that these critical issues could be decision variables of government, thus resulting in effective waste management.

Appendix 1 (Proof of Theorem 1)

In order to prove the convexity of distributor 1's cost with respect to csr_1, the first and second derivatives of C_{D1} are $\frac{\partial C_{D1}}{\partial \mathrm{csr}_1} = \vartheta \mathrm{csr}_1 + \left(\varsigma_1 - g\right)\gamma$, $\frac{\partial^2 C_{D1}}{\partial \mathrm{csr}_1^2} = \vartheta > 0$. The second derivative of C_{D1} with respect to csr_1 is positive. Therefore, C_{D1} is convex with respect to csr_1.

Appendix 2 (Proof of Theorem 2)

To prove the convexity of distributor 2's cost with respect to csr_2, the first and second derivatives of C_{D2} are $\frac{\partial C_{D2}}{\partial \mathrm{csr}_2} = \vartheta \mathrm{csr}_2 + \left(\varsigma_2 - g\right)\gamma$, $\frac{\partial^2 C_{D2}}{\partial \mathrm{csr}_2^2} = \vartheta > 0$. The second derivative of C_{D2} with respect to csr_2 is positive. Therefore, C_{D2} is convex with respect to csr_2.

Appendix 3 (Proof of Theorem 3)

To determine the convexity of the cost of SPRSC under the centralized model with respect to csr_1 and csr_2, the Hessian matrix of C_{cen} is as follows:

$$H = \begin{bmatrix} \frac{\partial^2 C_{\mathrm{cen}}}{\partial \mathrm{csr}_1^2} & \frac{\partial^2 C_{\mathrm{cen}}}{\partial \mathrm{csr}_1 \partial \mathrm{csr}_2} \\ \frac{\partial^2 C_{\mathrm{cen}}}{\partial \mathrm{csr}_2 \partial \mathrm{csr}_1} & \frac{\partial^2 C_{\mathrm{cen}}}{\partial \mathrm{csr}_2^2} \end{bmatrix} = \begin{bmatrix} \vartheta & 0 \\ 0 & \vartheta \end{bmatrix} > 0$$

$$\frac{\partial C_{\mathrm{cen}}}{\partial \mathrm{csr}_1} = (\gamma - \theta)\left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - b_1 \rho - b_2 T - G\right) + \vartheta \mathrm{csr}_1 + \gamma \varsigma_1 - \varsigma_2 \theta \tag{26}$$

$$\frac{\partial C_{\mathrm{cen}}}{\partial \mathrm{csr}_2} = (\gamma - \theta)\left(C_{\mathrm{seg}} + b_3 C_{\mathrm{dis}} - b_1 \rho - b_2 T - G\right) + \vartheta \mathrm{csr}_2 + \gamma \varsigma_2 - \varsigma_1 \theta \tag{27}$$

The first ($H_{11} = \vartheta > 0$) and the second ($H_{22} = \vartheta^2 > 0$) principals of the Hessian matrix are positive. Therefore, the SPRSC cost function is convex with respect to csr_1 and csr_2. Also, the minimum value of C_{cen} can be calculated by derivation.

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