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Collection disruption management and channel coordination in a socially concerned closed-loop supply chain: A game theory approach

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Abstract

Uncertainty in real-world situations disrupts operations, including the collection process in closed-loop supply chains (CLSCs). A collection disruption is more critical in the pharmaceutical sector since pharmaceutical leftovers contain chemicals that threaten the environment and human health. This paper revolves around the challenges of a real pharmaceutical case that implements circular economy principles through a closed-loop system design, takes sustainability issues into account, and seeks for effective management of collection disruption. The case includes a manufacturer, who invests in green research and development (R&D), and two retailers competing on corporate social responsibility (CSR) efforts to boost the collection amount and market demand. This competitive environment raises conflict of interests and complicates the interactions between members, which need to be neutralized by an appropriate coordination plan. This paper proposes an analytical scenario-based coordination model that resolves channel conflicts and pays dividends to the involving members through augmenting their social, economic, and environmental performance. We show that the coordination plan could be a practical policy to increase the system's adaptability to disruption. Under the coordinated model, by increasing a retailer's collection disruption, the other one invests more in CSR efforts to compensate for its competitor's lower collection, preventing loss for the whole channel. We also demonstrate that the proposed model maintains the chain's balance and prevents loss in case of a highly competitive CSR-based collection and boosts the collection amount, market demand, and the whole chain's profitability simultaneously.

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1. Introduction

Owing to the uncertain nature of many real-world situations, any process could face disruptions during operation (Choi et al., 2019); collection as a fundamental aspect of closed-loop supply chains (CLSCs) is not immune to disruption. Collection related disruptions may happen due to a wide array of issues, including natural disasters, such as tsunamis and earthquakes, fire, congestion at ports, customs software glitches, lack of capacity in the transportation facilities, and labor disputes (Li et al., 2016). Disruption is likely to damage the whole CLSC performance, diminish shareholders' wealth, or might even put small companies out of business (Gaustad et al., 2018). Perhaps the most recent example of disruption in supply chains is the recent COVID-19 pandemic, forcing many producers, such as Fiat Chrysler and Hyundai Automobiles, to suspend their productions (Malik and Sarkar, 2020). A collection disruption interrupts the collection process, which in turn influences the collector and may cause a significant loss to the upstream of the supply chain interacting with the collector. Besides, an efficient collection process is a critical prerequisite for CLSC development. Hence, it is of high significance to manage and mitigate the risk of collection disruption. Note that since pharmaceutical leftovers are likely to cause severe damages to the environment and endanger human health (Daughton, 2003), collection disruption in the pharmaceutical sector can be even more severe (Kabir, 2013).

A critical factor affecting the active performance of CLSCs is the collection amount (Shaharudin et al., 2015). Incentive policies are often needed to elevate customers' willingness to return used items and improve the collection amount. This is because few customers return their used products due to their social responsibility (Geyer and Blass, 2010). CSR activities, such as those increasing customers'
environmental awareness, can be proper incentive plans to induce customers to return their used items and boost the collection amount (Sarkis et al., 2010). CSR could be defined as the voluntary activities of a company exhibiting the interactions of day to day operations and social and environmental considerations (Van Marrewijk, 2003). In addition, exerting CSR improves the companies’ reputation and significantly influences customers’ goodwill (Komodromos and Melanthiou, 2014), which enhances the market demand (Hsueh, 2014). There are many examples of well-known firms of exerting CSR to make competitive advantage and sustainable products, such as Nike, Adidas, Gap, and Walmart (Nematollahi et al., 2017). In real networks, multiple members may participate in CSR activities at the same time. This causes competition between them and affects the CLSC performance (Zhang and Ren, 2016). CSR activities at the same time. This causes competition between them and affects the CLSC performance (Zhang and Ren, 2016).

Young and Rasti-Barzoki (2019a), and R&D investment is a significant decision variable in the pharmaceutical sector. In the United States, the ratio of R&D investment to sales revenue in the pharmaceutical industry is five times more than the average in all sectors (Nouri et al., 2018). The retailers assume the collection responsibility and boost the return amount by participating in CSR activities. Meanwhile, the above-mentioned CLSC faces substantial challenges, such as (i) aligning the conflict of interests and managing the complex interactions between the involved parties; (ii) acting in a competitive environment; and (iii) facing uncertainty of the collection process, caused by disruption, which frustrate the chain’s performance.

While supply, demand, and production disruptions have been widely studied in the literature (Guo et al., 2019; Huang and Wang, 2018; Han et al., 2017; Chen and Xiao, 2009; Giri and Sarker, 2016; Li et al., 2015), collection disruption is neglected by the previous researchers. However, collection disruption highly affects the performance of the CLSCs, since the successful performance of these systems depends on the effective management of the collection process and the reverse flow (Hosseini-Motlagh et al., 2019c). Contributing to the previous literature investigating disruptions in CLSCs, this study evaluates the performance of such systems in the face of collection disruptions. When the collection process is disrupted, (i) the retailers (collectors) collect lower items and lose some profit, and (ii) the manufacturer receives lower resources and incurs an extra cost. Therefore, in such a case, not only the retailers’ profit is affected, but also the manufacturer’s performance is exacerbated. In the literature, various promotional offers, such as purchase price (Balmus et al., 2014), reward-penalty (Wang et al., 2017), discount offer (Taleizadeh et al., 2019), economic incentives (Hosseini-Motlagh et al., 2020c), collection investment (Sabbaghnia and Taleizadeh, 2020), and acquisition price (Hosseini-Motlagh et al., 2020a), have been proposed to augment the collection amount of used products, while CSR participation has not been studied in this regard. We contribute to this literature and investigate the case where two competitive retailers exert CSR as an incentive policy to raise the consumers’ willingness to return their plastic containers, which also affects the demand for new products. Accordingly, these efforts determine both the raw material supply...
(derived from collected products) and the sales amount (demand) of the pharmaceutical manufacturer. As a result, the manufacturer’s performance depends also on the retailers’ decisions (Hosseini-Motlagh et al., 2020c). CSR participation of retailers causes competition between them and complicates the interactions within the chain. Besides, the DG Company tends to invest in green R&D efforts to produce more environmentally friendly products. Green R&D efforts influence the customer's tendency to buy the manufacturer’s products and thus influence the retailers’ demand in the investigated market (from a theoretical viewpoint, such impacts of these efforts are also addressed by the previous literature such as Levin and Reiss (1989)). Due to such interrelations between the members’ decisions, it is of high importance to implement a practical coordination mechanism to deal with CLSC challenges and manage the interactions between the members (Chen and Xiao, 2015). This study analytically explores the role of coordination models in enhancing the performance of such systems dealing with competition in both forward and reverse channels and facing disruptions. It is worth mentioning that such a scenario might occur in many companies and industries, and the proposed models are generalizable to any production system with similar attributes.

The primary purpose of this paper is to develop an analytical model to tackle the above-mentioned challenges of the investigated case, generalizable to similar production systems. To this end, the paper develops a scenario-based coordination model for tackling collection disruption, R&D efforts, and competitive CSR activities of two retailers in both forward and reverse channels. The model is investigated in the decentralized system, which indicates the current situation of the case. Since DG and the retailers determine their decisions individually, this setting leads to locally optimal solutions and frustrates the efficiency of the system. Afterward, the centralized decision-making structure is modeled, which gives a benchmark for measuring the best performance of the system. However, centralization is not acceptable for all members, since it maximizes the objective of the whole system and neglects the benefit of individual members. Therefore, to coordinate the system and ensure the members’ participation in the centralization, a profit-sharing mechanism is proposed, and the fairness of the profit-sharing is guaranteed by a simple Nash-bargaining model. Overall, the main contributions of this study are as follows:

- The present paper analytically analyzes collection disruption as a source of uncertainty in a pharmaceutical closed-loop supply chain (PCLSC).
- This study proposes competitive CSR participation of retailers as an incentive strategy to boost the collection volume and market demand of the PCLSC in forward and reverse channels, respectively.
- We develop a model for simultaneous coordination of competitive CSR efforts, collection disruption, and green R&D, implementing a profit-sharing contract and Nash-bargaining game model to ensure the fairness of the coordination scheme.
- Last but not least, this study revolves around a real pharmaceutical case and tries to manage the significant challenges of the case effectively. However, the proposed models are generalizable to any production system with similar attributes.

The rest of this study is arranged as follows. Section 2 contains the related literature review. Section 3 describes the investigated problem. Section 4 represents the objective functions under the scenario-based decentralized, centralized, and coordinated systems alongside the optimal R&D investment and competitive CSR efforts. Sections 5 and 6 demonstrate analytical and numerical results of a real case study in detail, respectively. Finally, Section 7 includes concluding remarks, managerial insights, and future research directions. All proofs are available in the Online Supplementary Appendix.

2. Literature review

In this section, we review the literature related to this paper. To this end, four research streams, i.e. (i) CLSCs and collection strategies in CLSCs, (ii) competition in CLSCs and channel coordination, (iii) CSR, and (iv) disruption management in supply chains and supply chain coordination are reviewed in separate sub-sections. Finally, research gaps and contributions of the study are explained.

2.1. CLSCs and collection strategies in CLSCs

Sustainability issues being widely noticed (Safarzadeh and Rasti-Barzoki, 2019b, 2020), many companies have decided to design a CLSC. In recent literature, various promotional offers have been proposed to augment the collection amount of used products by increasing the consumers’ willingness to return used products (Govindan et al., 2015). For instance, Bulmus et al. (2014) used purchase price as a customer incentive to increase the return rate. Additionally, Wang et al. (2017) evaluated a reward-penalty mechanism in a CLSC with two competing manufacturers. Taleizadeh et al. (2019) used a discount offer on the returned products so as to entice customers to bring back their used products. Hosseini-Motlagh et al. (2020c) introduced economic incentives, Sabbaghnia and Taleizadeh (2020) used collection investment, and Hosseini-Motlagh et al. (2020a) employed acquisition price as incentives for customers to return more items. Besides, some papers suggest that the incentive policies could not only raise the return quantity of used products but also affect the market demand for new products. For example, Das and Dutta (2013) illustrated that a product exchange plan applied to a CLSC improves the collection amount of used products as well as the total demand. However, to the best of our knowledge, CSR as an incentive plan has not been noticed in the literature, while it is currently applied in practice.

In the pharmaceutical sector, Ritchie et al. (2000) revealed the benefits of pharmaceutical reverse logistics for 28 hospitals in the UK, having the potential for considerable financial savings. Likewise, Khan and Subzwarei (2009) stated that developments in the reverse channels saved at least 10% of costs in the studied pharmaceutical system in Pakistan. The whole pharmaceutical supply chain benefits from medicines procurement associated with reverse logistics (Xie and Breen, 2014). However, improper coordination and collaboration between the involving parties are identified as the major hindrances in pharmaceutical CLSCs (Viegas et al., 2019; Ding, 2018).

2.2. Competition in CLSCs and channel coordination

Many researchers have investigated competition as a factor that dramatically affects the performance of CLSCs. For example, Jena and Sarmah (2014) investigated the competition on new product demand and the return rate of used products. They concluded that the channel achieves its best performance under a cooperative system. Qiang (2015) analyzed the effects of competition on the manufacturers’ market share. Fallah et al. (2015) investigated the Stackelberg competition on the retail prices and customer incentives between two CLSCs. Wang et al. (2018) considered two types of competition: (i) competition between collectors and (ii) competition between new and remanufactured products. Afterward, He et al. (2019) evaluated the competitive collection and recovery efficiency in both decentralized and centralized systems.
Hosseini-Motlagh et al. (2019c) coordinated a competitive reverse supply chain across multiple links. It is found that implementing supply chain coordination is remarkably useful in the presence of competing members (De Giovanni, 2018). However, the simultaneous effects of competition on both forward and reverse channels have not been adequately noticed in the channel coordination literature (Fallah et al., 2015).

2.3 CSR

CSR activities are becoming increasingly important in recent decades. Many scholars have investigated the effects of CSR efforts in supply chains. For instance, Nematollahi et al. (2017) implemented a collaborative mechanism to coordinate CSR investment decisions in a supply chain. Moreover, Panda et al. (2017) examined the effects of CSR in a CLSC. They demonstrated that channel coordination is a practical policy to share CSR costs between members and enhance the CSR performance level. The effect of different game structures in a socially responsible supply chain is studied by Seyedihosseini et al. (2019). Raj et al. (2018) coordinated greening and CSR activities and showed that sustainability is beneficial for companies. Raza (2018) coordinated a supply chain with price-CSR dependent demand in both deterministic and stochastic conditions. In addition, Hosseini-Motlagh et al. (2019b) coordinated a socially responsible supply chain through the lead time crashing contract. Modak et al. (2019) coordinated a CLSC, considering donation as a CSR activity and price-CSR sensitive demand. Johari et al. (2019) analyzed the long-term behavior of manufacturers to investigate which of the CSR or Non-CSR strategies are better to be adopted.

2.4 Disruption management in supply chains and supply chain coordination

Disruption as a result of uncertainty in the real cases damages the whole CLSC performance, and the research depth of this field is increasing in the literature. For instance, Jabbarzadeh et al. (2016) presented a supply chain resilient to supply, demand, and facility disruptions using a robust-stochastic optimization model. Moreover, Guo et al. (2019) investigated the probability of supply disruption and government subsidy in a CLSC. Likewise, Giri and Sharma (2016) studied uncertain demand and return rate in a hybrid CLSC. Then, a CLSC with remanufacturing cost disruption is developed by Wu et al. (2018). Besides, Li et al. (2016) studied the non-delivery penalty and financing assistance strategies for supply disruption in a supply chain. Song (2019) proposed an adjusted revenue-sharing contract to hedge against demand disruption in a closed-loop supply chain. To the best of our knowledge, disruption occurrence regarding the collection process, which is a significant issue in both theory and practice, has not been studied in the literature. Coordination plans are good means of improving the supply chain profitability (Hosseini-Motlagh et al., 2018) and balance the including parties’ conflict of interests (Yan et al., 2017). Therefore, many papers utilize this approach to manage disruptions in production systems. Here are some papers using coordination schemes to deal with disruptions in supply chains: Xiao and Qi (2008) managed cost and demand disruptions applying two different modified quantity discount contracts. Chen and Xiao (2009) also coordinated a supply chain under demand disruption by a linear quantity discount model. Then, Cao et al. (2013) used an improved revenue-sharing contract to deal with demand and cost disruption. Additionally, Mohammadzadeh and Zegordi (2016) coordinated a supply chain under supply disruption and uncertain market demand. Buyback and revenue-sharing contracts with production disruption are examined by Giri and Sarker (2017). A transshipment contract is developed by Aslani and Heydari (2019) in order to coordinate a supply chain under disruption probability. Although there are numerous papers that have coordinated a chain under disruptions, they neglect the important issue of CSR competition in both forward and reverse channels of their network and also, they lack the issue of collection disruption in their reverse channel, which is a critical hindrance to companies’ performance.

2.5. Research gaps and contributions

The above-reviewed studies illustrate the main contributions of this study as follows. First, different from the previous studies (Guo et al., 2019; Huang and Wang, 2018; Han et al., 2017; Chen and Xiao, 2009; Giri and Sarker, 2016; Li et al., 2015; Song, 2019), which have considered disruption regarding supply, demand, and production, this study is the first to investigate disruption occurring in the collection process in the channel coordination context. Second, while many papers have investigated competition on various decisions, such as acquisition price (Bulmüs et al., 2014), retail price, and customer incentive (Fallah et al., 2015), in either forward or reverse channels of a supply chain, studies on competition in both the forward and reverse channels are scarce (Fallah et al., 2015). However, to the best of our knowledge, this paper is the first to evaluate the effects of competitive CSR efforts on both the market demand and collection amount, as important practical and theoretical issues, in the context of supply chain coordination. Third, the previous studies in the CLSC coordination literature usually consider the collection amount to be dependent on incentives, such as discounts or acquisition prices, while in this paper, we propose the CSR participation as the factor influencing the collection rate. Besides, according to Campos et al. (2017), studies in the field of product reuse in the pharmaceutical industry are scarce, while the current paper suggests reusing products and green R&D as strategies toward achieving sustainability in the pharmaceutical sector. Moreover, it analyzes the effects of green R&D on market demand. Furthermore, this study implements a profit-sharing contract to coordinate the interactions of the mentioned elements in a two-echelon PCLSC, and the Nash-bargaining game model is applied to ensure the fairness of the coordination scheme. Table 1 and Fig. 1 highlight the current paper’s contributions compared to the previously published papers.

3. Problem description

A real PCLSC related to the DG Company (the pharmaceutical manufacturer) and its retailers is investigated in this paper. DG provides the medications in plastic containers and seeks to collect plastic containers from the customer zone in order to reuse them. To this end, DG assigns the collection responsibility to the retailers. The retailers try to motivate customers to return their empty plastic containers by doing CSR activities, such as raising public awareness about the detrimental effects of pharmaceutical leftovers on the environment. Moreover, the retailers compete on collecting the plastic containers by improving their CSR attempts. Thus, the collection function of retailer $(j)$ can be formulated as $R_j = a_j + b_j \xi_j - \gamma_{x_{3,j}} - 1 = 2$, where $\xi_j$ is the CSR investment level of retailer $(j)$, $a_j$ is the initial amount of plastic containers collected by retailer $(j)$, $b_j$ is the intrinsic CSR efforts elasticity coefficient of each retailer’s collection function, and $\gamma$ is the cross-CSR efforts elasticity coefficient of each retailer’s collection function. The total return quantity for DG is obtained by $R = \sum_{j=1}^{s} R_j$. The retailers inspect the collected items, deliver them to DG, and receive a collection fee per item returned. Afterward, the items go through inspection, cleaning, and disinfection processes before entering the production line at DG’s...
site.

CSR participation, such as increasing customer environmental awareness, not only affects the collection amount but also boosts the market demand of the retailers. Therefore, the retailers’ CSR competition arises in either forward channel or reverse channel of the PCLSC. Moreover, DG applies green R&D (e.g., considering environmental issues in drug formulation, manufacturing, and packaging) as an eco-friendly policy that affects the market demand, as well. The demand function for retailer \( j \) is formulated as:

\[
D_j = a + b x_j^e + e_j G^{\varphi}, \quad j = 1, 2
\]

where \( a \) is the initial demand of each retailer, \( b \) is the intrinsic CSR efforts elasticity coefficient of each retailer’s demand function, \( e \) is the cross-CSR efforts elasticity coefficient of each retailer’s demand function. The total demand of DG is obtained by:

\[
D = \sum_{j=1}^{2} D_j
\]

Note that due to health policies, the retail price and wholesale price of pharmaceutical products are under the control of the government, and therefore, the mentioned parameters are considered exogenous in this problem, which cannot be changed.

The collection process, as a significant aspect of the mentioned PCLSC, is prone to disruptions that could be caused by numerous unexpected incidents. Collection disruption occurrence lessens the return quantity, which in turn endangers the PCLSC objectives. Let \( 0 < p_j < 1 \) be the probability that retailer \( j \) faces disruption during the collection process. In such a case, retailer \( j \) is unable to collect and deliver plastic containers, and DG incurs an extra cost. To analyze the problem, four scenarios are considered based on disruption occurrence (Giri and Sarker, 2016):

- Scenario (1): No disruption occurs
- Scenario (2): Retailer (1) faces collection disruption, and no disruption occurs at retailer (2)
- Scenario (3): Retailer (2) faces collection disruption, and no disruption occurs at retailer (1)
- Scenario (4): The collection disruption happens for both retailers.

Overall, the DG Company seeks ways to: improve the collection amount of the used products, manage the competitive environment, deal with the uncertainty of the collection process, find the optimal R&D and CSR investment levels, and manage the

| Number | Papers | CLSC | Sustainable chain | Competition | Channel | Disruption |
|--------|--------|------|-------------------|-------------|---------|------------|
|        |        |      |                   | Forward channel | Reverse channel | Coordination | Supply | Demand | Production | Collection |
| 1      | Fallah et al. (2015) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 2      | Han et al. (2017) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 3      | Wu et al. (2018) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 4      | Wang et al. (2018) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 5      | Huang and Wang (2018) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 6      | Guo et al. (2019) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 7      | He et al. (2019) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 8      | Hosseini-Motlagh et al. (2019a) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 9      | Song (2019) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 10     | Hosseini-Motlagh et al. (2020c) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 11     | Hosseini-Motlagh et al. (2020a) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 12     | Sabbaghnia and Taleizadeh (2020) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 13     | Ghomi-Avili et al. (2020) | ✓    | ✓                 | ✓           | ✓       | ✓          |        |        |            |           |
| 14     | Our paper | ✓    | ✓                 | ✓           | ✓       | ✓          | ✓      | ✓      | ✓          | ✓         |
interactions between the involved parties. Therefore, the current study aims to find the optimal green R&D level and CSR investment decisions in a competitive CLSC system under different disruption scenarios. Moreover, this paper evaluates the channel coordination approach as a strategy to manage the interactive effects of DG’s green R&D efforts, the retailers’ competitive CSR practices, and disruption in the collection process. The scenario-based decentralized model of the investigated problem is developed under the Stackelberg game, considering the manufacturer as the leader, and the retailers as its followers. Afterward, the centralized decision-making system is devised as a benchmark for the best performance of the system, and then, a profit-sharing coordination scheme is proposed to coordinate the members’ decisions and ensures their benefit. The Nash-bargaining game is applied as the profit-allocation plan. Note that these scenarios may occur in various industries, and the proposed models are generalizable to any reverse channel with similar attributes. Fig. 2 schematically illustrates the CLSC under investigation.

3.1. Assumptions and notations

In this section, we explain the important assumptions considered in the proposed model.

Assumption 1. The demand and return functions are considered linear.

Assumption 2. \( (b > e), (\beta > \gamma), (p > w > c_j), \) and \( (0 < \delta_j, \omega, P_j < 1) \)

Intrinsic CSR efforts elasticity coefficients of each retailer’s demand and collection functions are greater than the cross-CSR efforts elasticity coefficient ones. Besides, the manufacturer sells the products to the retailer with a higher price than production cost, and the retailer sells the products to the customers at a higher price than the wholesale price (the retailer’s purchasing cost).

Assumption 3. 

Retailer \((j)’s\) marginal revenue from each returned item is obtained by \( \delta_j(p_r - c_i - c_j) - c_i \geq 0 \)

Assumption 4. 

The manufacturer’s marginal revenue from each returned item is obtained as \( \omega(c_f - c^m_f + c^m_d) - p_r - c^m_i - c^m_d \geq 0 \)

Assumption 5. The green investment cost of the pharmaceutical manufacturer is considered quadratic.

Similar to many related studies (Safarzadeh et al., 2020b; Hosseini-Motlagh et al., 2020b; Heydari et al., 2017), we consider a linear relation for the return and demand functions.

Fig. 2. The investigated CLSC.
4. Methodology and model

In this paper, the methodology of supply chain coordination with the profit-sharing contract is implemented. In a supply chain, there are two decision-making structures:

1. Decentralized: under the decentralized decision-making structure, each member makes decisions to optimize its benefit regardless of the other members’ profit. This individual decision-making model results in inefficient, locally optimal solutions. The reservation level of profits for each party is derived in the decentralized decision-making structure.

2. Centralized: the centralized decision-making structure is associated with the integrational management of members where the decisions are determined so as to maximize the total supply chain profit. Thus, the centralized decision-making structure leads to globally optimal solutions. Accordingly, the centralized structure as a benchmark reaches the best performance of the channel.

Supply chain coordination induces individual members to decide based on the centralized decision-making structure instead of their local decisions. To achieve the optimal decisions of the entire chain, a coordination mechanism places the centralized decisions into the objective functions that the individual parties have in the decentralized setting. This method guarantees to enhance the supply chain profit up to that of the centralized one (achieving channel coordination) while it simultaneously improves the profitability of each member compared to that of the decentralized structure. Since the Stackelberg game is played between the members, the backward induction method is applied to determine the decentralized optimal decisions. Hence, considering the manufacturer as the leader and the retailers as the followers, first, the retailers determine their CSR investment levels, and then the manufacturer determines their CSR investment levels, and then the manufacturer determines the green R&D investment level considering the retailers’ best responses.

4.1. Modeling disruption in the collection process

Disruption occurrence in the collection process lessens the return quantity collected by the retailers and affects DG’s performance, as well. Four different possible scenarios are presented in the following. The members’ objective functions are modeled considering each probable scenario and the effects of collection disruption. Afterward, the decentralized and centralized decision-making systems are examined based on these scenarios, and the PCLSC members’ decisions are coordinated. Then, the Nash-bargaining game model is proposed to allocate the earned profit to all members.

Here, the expected scenario-based profit functions under collection disruption are developed. We use $x_j = \delta_j(p_r - c_{Rj} - c_{Dj} - c_{pr})$ to denote retailer $(j)$’s marginal revenue from each returned item. Similarly, we can denote the manufacturer’s marginal revenue from each returned item as $y = \omega(c_{rz} - c_{rz}^0) - p_r - c_{rz}^0 - c_{rz}^0$. Note that $x_j$ and $y$ cannot be negative. Hence, conditions $\delta_j p_r - \delta_j(c_{Rj} + c_{Dj}) - c_{pr}^0 \geq 0$ and $\omega c_{rz} \geq p_r + c_{rz}^0 + \omega c_{rz}^0 + c_{rz}^0(1-\omega)$ hold, respectively. Moreover, we define a random variable to illustrate the effect of disruption as Eq. (1) shows:

$$\rho_j = \begin{cases} 0 & w.p. P_j \\ 1 & w.p. 1-P_j \end{cases}$$

$\rho_j$ is the proportion of collected items that are delivered to the manufacturer by retailer $(j)$ with respect to the collection disruption possibility. Accordingly, retailer $(j)$’s scenario-based profit can be formulated as Eq. (2):

$$\pi_{rj}(\xi_j) = E_p \left[ \rho_j x_j R_j(\xi_j, \xi_{3-j}) - (1 - \rho_j) F + (p - w - \xi_j) D_j(\xi_j, \xi_{3-j}, G) \right]$$

(2)

The first term in Eq. (2) shows the retailer’s earned revenue from selling the collected plastic containers to DG. The second term is the disruption cost which is related to the additional time to handle the disruption and resume the collection process (Mark et al.). The third term indicates the profit of selling medicines to the end customers in the forward channel, and the cost of CSR investment. Eq. (3) represents the manufacturer’s expected profit under the four disruption scenarios.

$$\pi_m(G) = E_{p_{3-j}} \left[ (w - c_r) D(\xi_j, \xi_{3-j}, G) + y \times \sum_{j=1}^{2} \rho_j x_j R_j(\xi_j, \xi_{3-j}) - \frac{1}{2} \nu G^2 \right]$$

(3)

The first term in Eq. (3) denotes the obtained revenue from selling new products, without using returned plastic containers. The second term indicates the gained revenue from selling new products using returned plastic containers of retailer (1) and (2). Finally, the last term shows the cost of investment in green activities. In the next subsections, the decentralized, centralized, and coordinated structures are investigated.

4.2. Decentralized structure

In the decentralized structure, members determine their decisions regardless of the PCLSC benefit. To be more specific, the manufacturer (DG) determines the green R&D level, and each retailer optimizes his CSR investment level, individually. Thus, for calculating the optimal values of decision variables, each member’s profit function is separately optimized. In the following subsections, we derive the members’ scenario-based decentralized profit function. Since the Stackelberg game is played between the members, the optimal green R&D level and competitive CSR efforts are obtained, subsequently, using the backward induction method. Note that in this study, the decentralized optimal solutions are represented using the superscript *, and the decentralized profit is indicated by superscript dec.

4.2.1. Retailer $(j)$ profit function

The retailers collect empty plastic containers and sell the medications to the customers. The collection amount and the market demand depend on the CSR investment level of the retailers. If the CSR investments grow, the retailers can benefit more from selling the plastic containers to the manufacturer and selling the medications to customers; but their costs increase as well. According to Eq. (2), the expected profit of retailer $(j)$ is as Eq. (4):

$$\pi_{rj}(\xi_j)_{dec} = D_j(p - w - \xi_j) + (1 - P_j) (\alpha_j + X_j + Y_j(\xi_{3-j}))$$

$$\times \left( \delta_j p_r - \delta_j(c_{Rj} + c_{Dj}) - c_{pr}^0 \right) - \nu F$$

(4)

In order to obtain the optimal value of retailer $(j)$’s decision variable, we optimize Eq. (4) with respect to $\xi_j$ and $\xi_{3-j}$ simultaneously, and the following Lemma is proposed.

Lemma 1. Retailer $(j)$’s objective function is concave with respect to $\xi_j$, hence the optimal CSR investment of retailer $(j)$ under the decentralized structure is obtained by Eq. (5):
\[ \xi_j = \frac{1}{4b^2 - e^2} \left( \left( 2b^2 + be \right) \left( p - w \right) - \left( 2b + e \right) \right) \times \left( a + Ck \right) + 2\beta b \left( P_j - 1 \right) \left( c_y + \delta_j \left( c_m + c_y - p_r \right) \right) + \beta e \left( P_{s-j} - 1 \right) \left( c_y + \delta_{s-j} \left( c_m + c_y - p_r \right) \right) \]  

\begin{equation}
\tag{5}
(\pi_{SC}(G, \xi_1, \xi_2))^\text{cen} = \pi_{ri}(\xi_j) + \pi_m(G)
\end{equation}

\[ (\pi_{SC}(G, \xi_1, \xi_2))^\text{cen} = D \left( p - c_j \right) - D_1 \xi_1 - D_2 \xi_2 - \frac{1}{2} \nu G^2 - (P_1 + P_2) F 
+ \left( P_2 - 1 \right) \left( c_y + \delta_2 \left( c_m + c_y \right) \right) \left( \alpha_2 + \beta \xi_2 - \gamma \xi_1 \right) + (P_1 - 1) \left( (P_2 - 1) \delta_2 \left( \alpha_2 + \beta \xi_2 - \gamma \xi_1 \right) + (P_1 - 1) \delta_1 \left( \alpha_1 + \beta \xi_1 - \gamma \xi_2 \right) \right) \right)
\begin{equation}
\tag{8}
(\pi_{SC}(G, \xi_1, \xi_2))^\text{cen} = \nu (c_m + c_y + c_e - c_i) - c_i^m - c_i^e
\end{equation}

\[ G^\ast = \frac{k}{2(k^2 + \nu (e - b))} \left[ 2b \left( c_y - p \right) - 2a - 2c_y e + 2e p \right. 
- \omega c_i \left( \beta - \gamma \right) \left( \delta_1 \left( P_1 - 1 \right) + \delta_2 \left( P_2 - 1 \right) \right) 
+ \left. \left( \beta - \gamma \right) \left( c_y^m \left( P_1 + P_2 - 2 \right) + \left( \delta_1 \left( P_1 - 1 \right) + \delta_2 \left( P_2 - 1 \right) \right) \right) \right]
\begin{equation}
\tag{10}
(\pi_{SC}(G, \xi_1, \xi_2))^\text{cen} = \nu (c_m + c_y + c_e - c_i) - c_i^m - c_i^e
\end{equation}

\[ (\pi_{SC}(G, \xi_1, \xi_2))^\text{cen} = \nu (c_m + c_y + c_e - c_i) - c_i^m - c_i^e
\end{equation}

\[ G^\ast = \frac{k}{2(k^2 + \nu (e - b))} \left[ 2b \left( c_y - p \right) - 2a - 2c_y e + 2e p \right. 
- \omega c_i \left( \beta - \gamma \right) \left( \delta_1 \left( P_1 - 1 \right) + \delta_2 \left( P_2 - 1 \right) \right) 
+ \left. \left( \beta - \gamma \right) \left( c_y^m \left( P_1 + P_2 - 2 \right) + \left( \delta_1 \left( P_1 - 1 \right) + \delta_2 \left( P_2 - 1 \right) \right) \right) \right]
\begin{equation}
\tag{11}
\end{equation}

The decentralized solutions are locally optimum determined by the including parties. Hence, to achieve the best system efficiency, the centralized model is proposed, where the decisions are made based on the whole system performance.

4.2.2. Manufacturer profit function

The manufacturer uses the returned amount in his production system in addition to the first handed plastic containers to satisfy the demand. Since the production cost decreases by using the returned items, the collection volume of retailers affects the production cost of the manufacturer. In other words, CSR participation of the retailers affects not only the manufacturer's sales amount but also his production costs. The manufacturer also invests in green R&D to produce more eco-friendly products and boost the market demand. The manufacturer's expected profit is modeled using Eq. (3) as follows:

\begin{equation}
(\pi_m(G))^\text{cen} = \nu \left( c_i + c_y \right) - c_i^m - c_i^e
\end{equation}

\[ \tag{6}
\end{equation}

Note that Eq. (5) shows that the retailers’ decisions, $\xi_j$, depend on the manufacturer's decision, $G$, and they are the followers of the Stackelberg game. According to the backward induction method, we replace the retailer's best responses from Eq. (5) in the expected profit of the manufacturer. Then, to obtain the optimal value of the manufacturer’s decision variable that maximizes Eq. (6) the following Lemma is proposed. Note that the retailers’ decentralized CSR investment is obtained by replacing the manufacturer’s final decision (Eq. (7)) into the retailers’ best response (Eq. (5)).

Lemma 2. The manufacturer’s profit function is concave with respect to $G$ under the decentralized structure, and the optimal green R&D efforts level is obtained by Eq. (7):

\[ G^\ast = \frac{k}{2(k^2 + \nu (e - b))} \left[ 2b \left( c_y - p \right) - 2a - 2c_y e + 2e p \right. 
- \omega c_i \left( \beta - \gamma \right) \left( \delta_1 \left( P_1 - 1 \right) + \delta_2 \left( P_2 - 1 \right) \right) 
+ \left. \left( \beta - \gamma \right) \left( c_y^m \left( P_1 + P_2 - 2 \right) + \left( \delta_1 \left( P_1 - 1 \right) + \delta_2 \left( P_2 - 1 \right) \right) \right) \right]
\begin{equation}
\tag{11}
\end{equation}

The decentralized solutions are locally optimum determined by the including parties. Hence, to achieve the best system efficiency, the centralized model is proposed, where the decisions are made based on the whole system performance.

4.3. Centralized structure

In the centralized system, the supply chain is considered as a single unit, and the decision variables (i.e., green effort and CSR levels) are optimized from an integrated viewpoint (Johari et al., 2018). In the previous literature on supply chain coordination, it is shown that shifting to the centralized system improves the performance of the entire chain (Heydari and Mosanna, 2018). The expected centralized profit function is the summation of the members’ scenario-based profit. Thus, the expected profit of the investigated supply chain is formulated as Eq. (8) (Chen and Xiao, 2015):
whole, the conflict of interests between actors is neutralized, and the disruption risk is mitigated through sharing with all supply chain members. Although the PCLSC achieves its best performance under the centralized structure, the benefit of each participant is not guaranteed. Consequently, centralization is usually inapplicable in practice, and a motivational plan is needed to encourage the reluctant members to make decisions based on the centralized setting (Choi and Liu, 2019).

4.4. Coordinated structure

Coordination strategies are employed to ensure all parties’ profitability and induce them to change their decentralized optimal solutions to the centralized ones. In our problem, three scenarios may occur after centralization: (1) the manufacturer benefits from centralization, while the retailers incur loss, (2) the retailers benefit under the centralized model, but the manufacturer incurs loss, and (3) all three members benefit from centralization, although the profit surplus is not fairly shared among them. Accordingly, a mechanism is needed to not only ensure profitability for all members but also fairly divide the profit surplus between all parties. To this end, in the current paper, a profit-sharing mechanism is proposed to coordinate the manufacturer’s green R&D efforts and the retailers’ competitive CSR practices along with the Nash-bargaining game model to ensure fairness. The profit-sharing contract is practically easy to implement and useful to channel coordination (Leng and Parlar, 2009). According to this mechanism, each member earns a proportion of the PCLSC profit under the centralized model. Let \( 0 \leq \theta_1 \leq 1 \) be the proportion of PCLSC profit given to retailer \((1)\), which leaves \(1 - \sum_{j=1}^{2} \theta_j\) for the manufacturer’s share. Accordingly, applying the profit-sharing contract, the members’ profit in the coordinated model is obtained as Eq. (12), Eq. (13), and Eq. (14) (Shao and Ji, 2009):

\[
\pi_{t_1}(\xi_1)_{\text{coo}} = \theta_1(\pi_{\text{SC}}(G, \xi_1, \xi_2))_{\text{cen}}
\]

(12)

\[
\pi_{t_2}(\xi_2)_{\text{coo}} = \theta_2(\pi_{\text{SC}}(G, \xi_1, \xi_2))_{\text{cen}}
\]

(13)

\[
\pi_m(G)_{\text{coo}} = (1 - \theta_1 - \theta_2)(\pi_{\text{SC}}(G, \xi_1, \xi_2))_{\text{cen}}
\]

(14)

Note that in our paper, superscript coo indicates the coordinated profit. The members’ coordinated profits must be greater than the decentralized ones to persuade the actors to accept the coordination. Therefore, the following conditions must be satisfied under the coordinated system. Eqs. (15) and (16) guarantee that retailer \((1)\) and retailer \((2)\) are inspired to cooperate in the coordination plan, respectively. Similarly, Eq. (17) ensures that the manufacturer is motivated to participate in the coordination scheme.

\[
\pi_{t_1}(\xi_1)_{\text{coo}} > \pi_{t_1}(\xi_1)_{\text{dec}}
\]

(15)

\[
\pi_{t_2}(\xi_2)_{\text{coo}} > \pi_{t_2}(\xi_2)_{\text{dec}}
\]

(16)

\[
\pi_m(G)_{\text{coo}} > \pi_m(G)_{\text{dec}}
\]

(17)

Accordingly, Lemmas 4 and 5 represent the lower bounds of \(\theta_1\) and \(\theta_2\), which are acceptable for retailer \((1)\) and retailer \((2)\), respectively. Note that retailer \((j)\) determines the minimum amount of \(\theta_j\) and any values of \(\theta_j\) lower than that is not acceptable, since it will not be beneficial to the retailers in the coordination plan.

**Lemma 4.** Based on Eq. (15), the minimum acceptable proportion of PCLSC profit given to retailer \((1)\) is shown by Eq. (18):

\[
\theta_1^{\min} = \left( \frac{\pi_{t_1}(\xi_1)}{\pi_{\text{SC}}(G, \xi_1, \xi_2)} \right)_{\text{cen}}
\]

(18)

**Lemma 5.** Based on Eq. (16), the minimum acceptable proportion of PCLSC profit given to retailer \((2)\) is shown by Eq. (19):

\[
\theta_2^{\min} = \left( \frac{\pi_{t_2}(\xi_2)}{\pi_{\text{SC}}(G, \xi_1, \xi_2)} \right)_{\text{cen}}
\]

(19)

Let \(S\) be the feasible range of \(\theta_1\) and \(\theta_2\) based on the above-mentioned conditions (Eq. (18) to (20)). Hence, for any \(\theta_1, \theta_2 \in S\), the coordination scheme is applicable. In such a case, not only the PCLSC achieves its best performance, but also the manufacturer and the retailers gain benefits. There are various methods to determine a fixed optimum solution for the contract parameters \(\theta_1, \theta_2\) in the previous literature (Nouri et al., 2018). The significant point is to fairly share the profit gained by the centralization between the members (Ebrahimii et al., 2017). The Nash-bargaining game model (Nash Jr, 1950) has been applied as the profit-allocation plan in different coordination contracts, such as profit-sharing (Yan, 2011), cooperative advertising (Li et al., 2002), and quantity discounts (Kohli and Park, 1989). The Nash bargaining cooperative game maximizes an objective function defined as the product of the bargainers’ profit (Panda et al., 2015). Moreover, each bargainer’s profit is the difference between the profit under the decentralized decision-making system and that of the coordinated one (Panda et al., 2015). The Nash bargaining solution reconciles efficiency and fairness in profit division. In this study, to calculate the exact optimum values of \(\theta_1\) and \(\theta_2\), a simple Nash-bargaining model is applied that guarantees a fair profit division between the members under the profit-sharing coordination mechanism. It is assumed that all three members are risk-neutral (Li et al., 2009). Lemma 7 states that the optimum values of \(\theta_1\) and \(\theta_2\) are obtained by solving Eq. (21), through the Nash-bargaining cooperative game model.

**Lemma 6.** The optimum values of \(\theta_1\) and \(\theta_2\) are derived by solving the following Nash-bargaining cooperative game model as the profit-allocation scheme:

\[
\theta_1^{\max} = 1 - \left( \frac{\pi_m(G)}{\pi_{\text{SC}}(G, \xi_1, \xi_2)} \right)_{\text{cen}}
\]

(20)
Max \( Z = \left[ (\pi_m(G))^{\text{coo}} - (\pi_m(G))^{\text{dec}} \right] \left[ (\pi_r(\xi_1))^{\text{coo}} - (\pi_r(\xi_1))^{\text{dec}} \right] \times \left[ (\pi_r(\xi_2))^{\text{coo}} - (\pi_r(\xi_2))^{\text{dec}} \right] \)  

(21)

5. Parametric analysis and discussion

To go deeper into the proposed model, this section provides an analytical sensitivity analysis on the coordinated and decentralized scenarios. We investigate how the variables of each setting behave when significant parameters of the model change. The results are presented in Propositions 1 to 4.

Proposition 1. Under the decentralized structure, the following results are derived regarding the retailers’ CSR participation. The level of CSR effort increases when the (i) probability of disruption in the collection process retailers are lower, (ii) fraction of acceptable items retailers’ are higher, (iii) intrinsic CSR efforts elasticity coefficient of each retailer’s collection function increases, (iv) cross-CSR efforts elasticity coefficient of each retailer’s collection function reduces, (v) wholesale price is lower, (vi) selling price and collection fee are higher, (vii) retailers’ operational costs (inspection, handling, and shipping costs) decrease, (viii) manufacturer’s green R&D efforts elasticity coefficient of demand increases, and (ix) green efforts cost-efficiency coefficient reduces.

According to Proposition 1, under the decentralized scenario, by increasing the probability of disruption occurring in the collection process of one retailer, the other retailer’s CSR investment level decreases, as well. This is because, when one retailer is weaker due to the collection disruption occurrence, its competitor is confident of its superiority and is not motivated to invest more in CSR. Moreover, by increasing the fraction of acceptable items in each retailer’s collection amount, the collection process is more beneficial, and thus, the retailer tends to invest more in CSR efforts and collect more items. This means that the retailer becomes a stronger competitor, which leaves the other retailer no choice but to participate more in the CSR activities and collect more items due to the competitive environment. Besides, a higher collection fee paid by the manufacturer improves the retailers’ revenue and their ability to invest more in CSR efforts. In such a case, more CSR activities are performed, customers are encouraged to return more empty plastic containers, and the collection amount is improved. Additionally, increasing the wholesale price raises the retailers’ costs and makes it more difficult for them to invest in CSR activities.

Proposition 2. Under the decentralized structure, the following results are derived regarding the manufacturer’s green R&D decision. The level of green R&D increases when the (i) wholesale price and collection fee are higher, (ii) production cost using first handed plastic containers reduces, (iii) manufacturer’s reverse operational costs (disposal, inspection, and production cost using returned plastic containers) increase, (iv) demand sensitivity to green efforts increases, (v) green efforts cost efficiency coefficient reduces, (vi) intrinsic CSR efforts elasticity coefficient of each retailer’s collection function decreases, (vii) intrinsic CSR efforts elasticity coefficient of each retailer’s demand function increases, (viii) probability of disruption occurring in the collection process of each retailer increases.

In the decentralized structure, the manufacturer’s marketing strategy (e.g., the wholesale price and the collection fee) has a direct influence on its green R&D activities. For instance, when the retailers receive a higher collection fee, they participate more in CSR activities (see Proposition 1), which in turn augments the manufacturer’s revenue and its green activities. Furthermore, when the customers’ sensitivity to green efforts is high, the manufacturer enhances its green efforts level to improve the demand and profitability of the chain. Likewise, when the customers are more sensitive to the CSR efforts, the sales amount, and the return quantity increase, the manufacturer’s revenue improves, and it can invest more in green R&D. Meanwhile, increasing the manufacturer’s reverse operational costs, decreasing the collection sensitivity to the retailers’ CSR efforts, and increasing the probability of disruption in the collection process reduce the retailers’ CSR participation and the collection amount. Thus, to compensate for the associated loss, the manufacturer invests more in R&D activities and increases the demand.

Proposition 3. Choosing the coordination scenario, the following results are derived regarding the retailers’ CSR decisions. (a) The positive effect of increasing the selling price on the CSR investment increases compared to the decentralized scenario, i.e., \( \frac{\partial v^*}{\partial p^*} > \frac{\partial v^*}{\partial p^*} \). (b) The level of CSR effort increases when the (i) probability of disruption in the collection process of each retailer is lower, (ii) probability of disruption occurring in the collection process of each retailer’s competitor is higher, (iii) fraction of acceptable items in each retailer’s collection amount is lower, (iv) fraction of acceptable items in the collection amount of each retailer’s competitor is lower, (v) selling price increases, and (vi) retailers’ operational costs decrease.

According to Proposition 3, as opposed to the decentralized structure, by increasing the probability of collection disruption at each retailer, the other retailer’s centralized CSR investment level increases to compensate for the reduction of the collected amount from the chain’s perspective. Moreover, by growing one retailer’s acceptance rate, the other one participates less in the CSR activities and collects fewer items to maintain the balance in the PCLSC. Therefore, the coordination mechanism keeps the PCLSC in balance when the probability of disruption and the fraction of acceptable items changes. Moreover, reducing the retailers’ selling price decreases their CSR activities at a lower rate compared to the decentralized one. Accordingly, channel coordination is an effective strategy to prevent loss in case of changing the selling price in the pharmaceutical market. Note that in the pharmaceutical market, while the demand is not sensitive to the selling price for the pharmaceuticals are regarded as essential goods (Guennif and Ramani, 2012), the price is often determined by the government or health organizations. Therefore, the PCLSC should be prepared to prevent the probable loss in case of decreasing the selling price by the government.

Proposition 4. Choosing the coordination scenario, the following results are derived regarding the manufacturer’s green R&D decision. (a) When the reverse operational costs and the probability of collection disruption grow, green R&D investment of the manufacturer enhances with a higher rate, i.e., \( \frac{\partial v^*}{\partial p^*} > \frac{\partial v^*}{\partial p^*} > \frac{\partial v^*}{\partial p^*} > \frac{\partial v^*}{\partial p^*} \), and \( \frac{\partial v^*}{\partial p^*} > \frac{\partial v^*}{\partial p^*} \). (b) The level of green R&D increases when the (i) selling price is higher, (ii) production cost using first handed plastic containers is lower, (iii) reverse operational costs are higher, (iv) intrinsic CSR efforts elasticity coefficient of each retailer’s collection function decreases, and (v) probability of disruption occurring in the collection process of each retailer increases.

Unlike the decentralized structure, increasing the selling price positively affects the manufacturer’s ability to invest in green efforts under the coordinated model. In both the decentralized and coordinated models, by increasing the reverse operational costs and the probability of collection disruption, the manufacturer
invests more in green R&D activities to compensate for the associated loss and increase the demand. However, in the coordinated system, this increasing rate is higher than that of the decentralized one. In other words, channel coordination helps the manufacturer to adapt himself in case of disruption in a more effective way compared to the decentralized setting. By improving the green R&D investment level, the PCLSC’s environmental sustainability improves, which is another achievement of the coordination strategy toward sustainability.

Overall, the above-mentioned propositions discuss how the coordination and decentralized optimal decisions behave with respect to the changes in the main parameters of the model. We conclude that compared to the decentralized structure, coordination (i) lessens the negative effects and strengthens the positive effects of changing model parameters on the PCLSC performance, and (ii) is a reasonable means of simultaneously moving toward the economic, environmental, and social goals of sustainability.

6. Applicability assessment of the proposed model: (A case study)

This section numerically examines the developed models using the collected data from the DG Company. However, some parameters are estimated based on the opinion of DG’s experts, since they are difficult to be accurately measured. In fact, the intrinsic CSR efforts elasticity coefficient of each retailer’s demand, cross-CSR efforts elasticity coefficient of each retailer’s demand, manufacturer’s green R&D efforts elasticity coefficient of demand, intrinsic CSR efforts elasticity coefficient of each retailer’s collection function, and cross-CSR efforts elasticity coefficient of each retailer’s collection function are designed to be consistent with the model assumptions and the experts’ opinions.

The DG Company implements a closed-loop system, invests in green R&D, and seeks for effective management of the system under collection disruption. The DG Company produces “Tolidin” in plastic containers and distributes them through duopolistic competing retailers. The two retailers compete on CSR efforts to boost the collection amount and market demand. The plastic containers are collected by the retailers and delivered to DG to re-enter the production line. The manufacturing cost is \( c_{f} = 5 \) $/unit using first handed plastic containers. DG sells Tolidin to the retailers with the wholesale price of \( w = 15 \) $/unit, and the retailers sell it with the selling price of \( p = 30 \) $/unit to the customers. DG tends to promote the sustainability level of the system via reusing its plastic medication containers and investing in green R&D. DG invests in the green R&D with the cost of \( r = 140 \) $/unit and boosts the demand with the rate of \( k = 10 \). Besides, the two retailers assume the collection responsibility and increase the return amount by participating in CSR with the rate of \( \beta = 60 \). The retailers’ CSR efforts boost the demand with the rate of \( b = 82 \), as well. Moreover, the retailers face disruption in their collection process with the probability of \( P_{1} = 0.5 \) and \( P_{2} = 0.4 \) for retailers (1) and (2), respectively. Collection disruption leads to the cost of \( F = 200 \) $/unit for both retailers. The retailers inspect the collected products with the cost of \( c_{f}^{n} = 0.3 \), and the fraction of acceptable items after the retailers’ inspections are \( \delta_{1} = 0.85 \) and \( \delta_{2} = 0.8 \) for retailers (1) and (2), respectively. The acceptable items are sold to DG with the collection fee of \( p_{c} = 3 \) $/unit with the shipping cost \( c_{f} = 0.1 \). DG also inspects the purchased containers with the cost \( c_{f}^{n} = 0.3 \) and the fraction of reusable containers which can enter the product line is \( \omega = 0.97 \). The manufacturing cost for DG when reusing the collected containers is \( c_{f}^{r} = 1.1 \) $/unit. The whole data of the company are indicated in Table 2.

The results of running the proposed model are indicated in Table 3.

Insight 1. Centralization improves green R&D and CSR activities, boosts the market demand and return quantity, benefits the manufacturer as well as the whole channel, and harms the retailers’ profitability.

Under the centralized structure, the PCLSC achieves its best sustainability performance, since the profitability of the entire channel, CSR activities, green R&D investment, and collection amount are enhanced, simultaneously. To be more specific, the chain profit increases from 43063.6 to 45817.4. CSR participation level of retailer (1) enhances from 3.67 to 7.75, CSR investment level of retailer (2) improves from 3.71 to 7.81, and DG’s green efforts level increases from 0.75 to 2.45 after centralization. As a consequence, the total market demand is changed from 1986.71 to 2609.94, and the total collection amount is increased from 724.22 to 1133.3. Along with these remarkable achievements, DG’s profit is enhanced from 19976.8 to 25909 by shifting to the centralized model.

However, after centralization, retailer (1)’s profit reduces from 11478. to 9894.71, and retailer (2)’s profit reduces from 1608.8 to 10013.6. Therefore, to convince the retailers to make globally optimal decisions, an incentive policy is needed. Using the profit-sharing mechanism along with the Nash-bargaining profit-allocation scheme, all members benefit from centralization, and the profit surplus is shared fairly between them. In other words, after coordinating the channel, DG’s profit increases from 19976.8 to 20894.7, retailer (1)’s profit increases from 11478. to 12395.9, and

### Table 2

The data of DG Company.

| Demand function parameters (Units/year) | Collection function parameters (Units/year) | Manufacturer operational costs ($/unit) | Retailers costs ($/unit) | Prices ($/unit) | Acceptance rates | Disruption parameters | Investment costs ($/unit) |
|----------------------------------------|---------------------------------------------|----------------------------------------|--------------------------|----------------|-------------------|-----------------------|--------------------------|
| \( a = 720 \)                          | \( a_{1} = 150 \)                           | \( c_{f}^{n} = 1.1 \)                  | \( c_{f}^{r} = 0.3 \)     | \( c_{f} = 5 \) | \( w = 15 \)     | \( P_{1} = 0.5 \)   | \( v = 140 \)            |
| \( b = 82 \)                           | \( a_{2} = 205 \)                           |                                         |                          |                |                   |                       |                          |
| \( c = 10 \)                           | \( b = 60 \)                                |                                         |                          |                |                   |                       |                          |
| \( k = 10 \)                           | \( \gamma = 10 \)                           |                                         |                          |                |                   |                       |                          |

### Table 3

Results of running the models in three different decision-making structures.

| Decentralized structure | Centralized structure | Coordinated structure |
|------------------------|----------------------|-----------------------|
| \( G \) 0.75           | 2.45                 | 2.45                  |
| \( \xi_{1} \) 3.67     | 7.75                 | 7.75                  |
| \( \xi_{2} \) 3.71     | 7.81                 | 7.81                  |
| \( D_{1} \) 991.38     | 1302.37              | 1302.37               |
| \( D_{2} \) 995.32     | 1307.58              | 1307.58               |
| \( D \) 1986.71        | 2609.94              | 2609.94               |
| \( R_{1} \) 333.11     | 537.16               | 537.16                |
| \( R_{2} \) 391.11     | 596.13               | 596.13                |
| \( R \) 724.22         | 1133.3               | 1133.3                |
| \( (\tau_{1}) \) 11478 | 9894.71              | 12395.9               |
| \( (\tau_{2}) \) 11608.8 | 10013.6          | 12526.7               |
| \( (\tau_{a}) \) 19976.8 | 25909              | 20894.7               |
| \( (\tau_{c}) \) 43063.6 | 45817.4          | 45817.4               |

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retailer (2)’s profit improves from 11608.8 to 12526.7. Hence, all parties are willing to participate in the coordination plan. The developed mechanism (i) advances the economic performance of the PCLSC, as well as each member; (ii) improves the sustainability performance of the PCLSC through enhancing CSR investment level and green efforts; and (iii) enhances the market demand and collection amount, simultaneously.

Insight 2. The coordination plan is capable of dealing with competitive CSR-based demand.

Fig. 3 analyses the influences of changing cross-CSR efforts elasticity coefficient of each retailer’s demand (e) on the PCLSC profit, demand, and the retailers’ CSR investment level in all decision-making structures. As Fig. 3 depicts, by augmenting e, the retailers’ CSR investment level decreases under the coordinated structure. However, the CSR levels in the coordinated model are considerably higher than those of the decentralized one for any rational values of e. When e grows, decreasing the retailers’ CSR investment reduces the market demand and, consequently, reduces the PCLSC profit. Meanwhile, in the coordinated model, the PCLSC demand and profit are more than those of the decentralized one, and the coordination scheme is useful for dealing with a competitive environment. Furthermore, the model is robust with respect to changing e within the interval [0, 39], since in this interval, the system is performing better under the coordination strategy compared to the decentralized structure.

Insight 3. The coordination model prevents loss in case of a highly competitive CSR-based collection.

Fig. 4 demonstrates the influences of changing cross-CSR efforts elasticity coefficient of each retailer's collection function (γ) on the PCLSC profit, the collection amount, and the retailers’ CSR investment level in all decision-making structures. Augmenting γ reduces the retailers’ CSR investment levels since the effect of each retailer’s attempts are neutralized by its competitor’s efforts. Consequently, the collection amount and the whole PCLSC profit decrease. However, shifting to the centralized optimal decisions with the help of the proposed coordination mechanism leads to a remarkable increase in the PCLSC profit, collection amount, and CSR activities for any rational values of γ, in comparison with the decentralized system. Therefore, the coordination plan can be a useful strategy to prevent loss in case of a highly competitive environment and maintain the best sustainability performance. Moreover, the model is robust with respect to γ within the interval [0, 60] since the coordinated collection amount is higher compared to that of the decentralized structure, and the proposed model is performing better from the environmental viewpoint. However, for any values of γ beyond 60, the coordinated profits and CSR investment levels of the chain members are higher than those of the decentralized model.

Insight 4. The coordination scheme can hedge against the negative effects of collection disruption on the PCLSC and each member’s performance.
The impacts of changing the probability that retailer (1) faces disruption during the collection process ($P_1$) on the model are indicated in Fig. 5. When $P_1$ increases, retailer (1) faces a higher risk of disruption, which lessens the retailer’s collection amount under all decision-making models. In such a case, retailer (1), and the whole PCLSC incur loss. Nevertheless, for any logical values of $P_1$, retailer (1)’s collection amount and profit, as well as the PCLSC profit in the coordinated system, are more than those of the decentralized one. Furthermore, in the coordinated structure, by increasing $P_1$, retailer (2) increases its collection amount to compensate for the lower collection amount of the other retailer and maintain the PCLSC sustainability performance (see also Proposition 3). This augmentation rate is higher in the coordinated model compared to the decentralized one. Therefore, the coordination scheme is able to decrease the adverse effects of collection disruption on the PCLSC and each member’s performance. According to Fig. 5, retailer (1)’s centralized profit is less than that of the decentralized one, which means that it will not participate in the centralization without an appropriate incentive plan. After implementing the coordination mechanism, however, the retailer’s profit improves compared to the decentralized system, which verifies applicability of the model. It is noteworthy that the influences of changing $P_2$ on the model is similar to those of $P_1$. Besides, the model is always robust with respect to the effects of changing $P_2$, since in the feasible interval of $P_2$, i.e., [0, 1], the performance of the proposed coordination model is considerably better compared to the decentralized one. This is because the negative effects of collection disruption on the system are minimized, and the chain enjoys a higher benefit alongside a higher social and environmental performance for any disruption possibility.

**Insight 5.** The coordinated model is remarkably more efficient in achieving the environmental goals of sustainability.

Fig. 6 indicates the effects of changing demand sensitivity to DG’s green efforts ($k$) on the PCLSC profit, market demand, and DG’s green efforts. By increasing $k$, customers’ sensitivity to green efforts has a more substantial positive effect on market demand. As a result, DG is motivated to invest more in the green R&D activities, which consequently augments the market demand and the PCLSC profit in all decision-making structures. Additionally, in the coordinated model, the market demand, DG’s green efforts, and the PCLSC profit, as well as their augmentation rates, are higher than those of the decentralized one for any values of $k$. Fig. 6 shows that the developed coordination model is more efficient regarding the environmental and economic aspects of sustainability compared to the decentralized one. Additionally, it is noteworthy that the proposed model is robust with respect to $k$, since the coordinated system is of higher environmental and economic performance compared to the decentralized structure.

**Insight 6.** The coordination plan can improve the chain’s performance even under high production costs.

Fig. 7 illustrates the effects of increasing the manufacturer’s unit production cost reusing returned plastic containers ($c_r^m$) on the model under all decision-making structures. Increasing $c_r^m$
decreases the manufacturer’s profit from reusing the products. In the coordinated model, this reduction affects the retailers’ CSR efforts and collection amount, since reusing the products is less beneficial from the economic viewpoint. However, even for high values of $c_m$, the coordinated model improves the chain’s sustainability performance. Furthermore, although the PCLSC profit decreases in all scenarios, the PCLSC profit in the coordinated model is greater than that of the decentralized one. Moreover, the model’s robust interval with respect to $c_m$ is considered $[0, 7.3]$, since for any values of $c_m$ beyond 7.3, the decentralized profits are negative, and the system incurs loss. However, the proposed coordination scheme is particularly useful and prevents loss when the production cost is high.

**Insight 7.** The coordination scheme prevents loss in case of reducing the selling price due to the health policies of the government.

Fig. 8 demonstrates the influences of changing the selling price ($p$) on the retailer (1)’s profit, the collection amount, and the manufacturer’s green R&D investment level in all decision-making structures. Augmenting $p$ enhances the revenue of the retailer and manufacturer. Consequently, the retailer’s profit and collection amount and the green R&D level improve. However, under the decentralized structure, the manufacturer’s green R&D is independent of the selling price (see also Proposition 2). Moreover, shifting to the centralized optimal decisions with the help of the proposed coordination mechanism leads to a remarkable increase in the retailer’s profit, collection amount, and green R&D activities for any feasible values of $p$, in comparison with the decentralized system. Besides, if the government reduces the selling price due to the health policies, the retailer loses its profitability and collection amount under the decentralized structure. However, shifting to the coordination strategy makes the PCLC safe to the changes in the selling price. Therefore, the coordination plan can be a useful strategy in the pharmaceutical sector to prevent loss in case of reducing the selling price due to the health policies. It is noteworthy that the influences of changing $p$ on the retailer (2)’s profit and collection are similar to those of retailer (1). Furthermore, the model is robust with respect to $p$ within the interval [9, 32]. This is because the retailers’ decentralized profits are negative for any values of $p$ lower than 9, and the retailers’ decentralized profits are higher than the coordinated ones for any values of $p$ higher than 32. However, for rational values of the selling price, the proposed coordination model is of higher sustainability performance compared to the decentralized structure.

**Insight 8.** When $\theta_j$ is equal to its maximum level, retailer (j)’s coordinated profit is maximum, and when $\sum_{j=1}^{2} \theta_j$ is equal to its maximum, the manufacturer’s coordinated profit is minimum.

Fig. 9 indicates the effects of changing the profit-sharing factors $(\theta_1, \theta_2)$ on the profit division among the three members. Using the data of Table 2, $\theta_1^{\text{min}} = 0.25$ is calculated using Eq. (18), and $\theta_2^{\text{min}} = 0.253$ and $(\theta_1 + \theta_2)^{\text{max}} = 0.56$ are calculated using Eqs. (19) and (20), respectively. Therefore, the feasible intervals for $\theta_1$ and $\theta_2$ are considered $[0.25, 0.307]$ and $[0.253, 0.31]$, respectively. Point C: $(0.25, 0.253, 22774)$ in Fig. 9 depicts that when $\theta_1$ and $\theta_2$ are minimum, DG’s coordinated profit is maximum. Likewise, point D: $(0.25, 0.303, 13754)$, where $\theta_2$ is maximum and $\theta_1$ is minimum, retailer (2)’s coordinated profit is maximum, and retailer (1)’s
coordinated profit is minimum. Point A: (0.3, 0.253, 13884) shows that when \( q_1 \) is maximum and \( q_2 \) is minimum, retailer (1)'s coordinated profit is maximum, and retailer (2)'s coordinated profit is minimum. Also, DG's share is minimum, when \( q_1 \) and \( q_2 \) are maximum (Point B: (0.3, 0.303, 18194)).

### 6.1. Managerial implications

This paper's managerial insights, derived from the numerical and analytical results, are provided hereunder.

Reverse supply chain managers can hedge against the negative effects of collection disruption on the system performance by an appropriate coordination scheme. Under the coordinated model, the system is more adaptable to disruption probability and can deal with the collection disruption more effectively in comparison with the decentralized structure. Under the coordinated model, if the probability of collection disruption occurrence for a retailer increases, the other one invests more in CSR efforts to compensate for its competitor's lower collection amount as well as preventing loss for the PCLSC.

Reverse supply chain managers can prevent loss and maintain balance in case of a highly competitive CSR-based collection by an appropriate coordination mechanism. Implementing the coordination plan is necessary for retailers, especially in highly competitive environments. This is because the coordination scheme reduces the negative impacts of competition on demand, CSR investments, and members' profits. Moreover, under the decentralized structure changing one retailer's CSR investment level is independent of the other retailer's acceptance rate. On the other hand, in the coordinated model, when one retailer's acceptance rate decreases, its opponent will participate more in the CSR activities and collect more items to maintain the balance in the PCLSC. Accordingly, the coordinated structure effectively keeps the PCLSC in balance when the retailer's acceptance rate changes.

Managers of production systems can move toward achieving the sustainability goals through an appropriate coordination model. Implementing the coordination plan increases the sustainability performance of the PCLSC through enabling the PCLSC members to invest more in their sustainability efforts, including CSR investment level and green efforts, and also enhances the market demand and collection amount, at the same time.

Overall, these achievements ensure sustainability through improving the economic, social, and environmental performance of the supply chain. In other words, the coordination plan is capable of protecting the environment from detrimental impacts of discarded pharmaceutical plastic containers, increasing the customers' willingness to return empty plastic containers, as well as ensuring profitability for the PCLSC and its members.

### 7. Concluding remarks

Similar to any other operations in the real world, the retailers' collection process is prone to disruption. This issue is of more significance in the pharmaceutical sector since pharmaceutical leftovers contain chemicals that threaten the environment and human health. Meanwhile, growing social and environmental concerns have forced companies to take sustainability issues into account in their decisions (Safarzadeh et al., 2020b). This study analyzes a real PCLSC that reuses its plastic containers, considering disruption in its collection process. The case includes a pharmaceutical company, namely DG, and two competitive retailers. However, the proposed models are generalizable to any production system with similar
attributes. Following a new approach, we assume that the retailers competitively exert CSR to increase the customers' tendency to return their used products, which simultaneously influence the market demand and the return quantity of empty plastic containers transferred to DG. Hence, when retailers participate less in CSR efforts, DG receives fewer products, which may lead to a shortage of resources. Moreover, DG performs green R&D activities, which boosts the market demand. Due to such interrelations between the members' decisions, the interactions of the members' decisions need to be coordinated to achieve an efficient system.

The problem is analytically investigated in three decentralized, centralized, and coordinated decision-making structures, through developing scenario-based mathematical models. The PCLSC members are coordinated, employing a profit-sharing mechanism, and fairness is guaranteed using a simple Nash-bargaining model. In addition, we analytically explore the circumstances that reusing plastic containers is beneficial for all parties, from both economic and environmental aspects. The current paper reveals that when the probability of disruption of a retailer grows under the coordinated model, the other one makes more CSR efforts to compensate for its competitor's lower collection, which prevents loss for the PCLSC. Accordingly, the system is more adaptable to disruption compared to the decentralized structure. Moreover, the coordination scheme reduces the negative impacts of competition on demand, CSR investments, and members' profits. It also maintains the system in balance when the retailer's acceptance rate changes. The coordination plan increases the sustainability performance of the PCLSC through enabling the PCLSC members to invest more in their sustainability efforts, including CSR investment level and green efforts, and also enhances the market demand and collection amount, at the same time.

Similar to other studies, this study is not without limitations. For example, this paper assumes that the operational costs, green efforts costs, and CSR investment costs are known to all parties. However, in many real situations, the supply chain members usually do not share these types of information with other parties. Hence, further studies could develop the investigated model considering asymmetric information. Also, since extra transportation regarding the collection process could harm the environment, the effects of transportation on environmental sustainability is an attractive issue to study in the context of supply chain coordination. Further studies may also consider an innovative distribution function for the collection disruption, as well. For example, they can assume that the probability of disruption occurrence is a function of facility boosting investment that protects the chain from potential disruptions.

Fig. 7. The effects of changing $c^m$ on the model.
Fig. 8. The influences of changing $p$ on the model.

Fig. 9. The effects of changing $q_1$ and $q_2$ on the members' profit allocation.
CRediT authorship contribution statement

Seyyed-Mahdi Hosseini-Motlagh: Conceptualization, Supervision, Formal analysis. Nazanin Nami: Methodology, Writing - review & editing. Zeinab Farshadfar: Investigation, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124173.

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