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Research article

A closed-loop green supply chain with retailers' competition and product recycling in the green environment under the cap-and-trade policy

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Abstract: Nowadays, product recycling has become an effective strategy for manufacturing industries to achieve sustainable development due to the scarcity of natural resources, waste management, and greenhouse gas emissions. This study considered an imperfect production-based competitive supply chain model for product recycling in an emission-reduction environment under a cap-and-trade scheme. The manufacturer invests in green technology to restrict carbon emissions during production. The recycler collects used items at a recovery rate depending on the buy-back price and environmental awareness effort. The rival retailers compete against each other for the retail price and promotional effort. The linear type of market demand depends on the retail price, promotional effort, and green level of the product. The proposed model was analyzed analytically and numerically under one centralized system, five decentralized systems, three Stackelberg, and two Nash game structures. Numerical examples and sensitivity analysis of the key parameters were studied to justify the feasibility of the proposed model. The present study revealed that the centralized scenario is mostly preferable for supply chain profit. The manufacturer-Stackelberg 1 scenario is most profitable for the manufacturer, whereas the two retailers collect maximum individual profit in the vertical Nash 2 model, where they jointly play the game. Moreover, retail price plays a crucial role in optimizing individual retailers' profits in the competitive market. In connection with the environmental aspects, the government should offer lower carbon caps to curtail excessive emissions and restrict the selling of excess carbon quotas.

Keywords: green investment; competitive supply chain; product recycling; environmental awareness effort
JEL Codes: Q4, Q5,C7

Abbreviations

CE: Carbon emissions; CT: Cap-and-trad; GT: Green technology; PE: Promotional effort; SCnM: Supply chain model; EA: Environmental awareness; PR: Product recovery; EA_e: Environmental awareness effort; RP: Retail price; CLSC: Closed-loop supply chain; CS: Centralized system; DS: Decentralized system

1. Introduction

In the 21st century, humankind is being threatened by the current state of environmental degradation. Emissions of gases and waste generation from industries, overpopulation, and other types of environmental pollution created by human activity are mainly responsible for environmental degradation. People in the current scenario are increasingly attracted to green products due to numerous health issues from environmental pollution, environmental degradation, etc. Global warming is one of the most significant environmental issues caused by industrial carbon emissions (CE). The governments of many areas,including China, the United States, and Europe have taken initiatives and implemented effective policies to curb emissions and make the public aware of eco-friendly products. In response to government pressure and the growing desire for green products, supply chain managers invest in green innovation technologies to reduce emissions and find innovative ways to manufacture low-carbon products. The global computer producer Dell modeled a tool to assess environmental risk toward a smaller ecological footprint in the supply chain and identified energy efficiency improvement technologies to lower greenhouse gas emissions to meet sustainability requirements[*].

The cap-and-trade (CT) policy is a significant and effective emissions-controlling strategy compared with other regulations initiated by the government. In this policy, the government assigns an emissions cap to the manufacturing industries for a mentioned period and issues a quantity of emission allowances consistent with the cap. The government charges excess emissions costs from the production industries over the defined cap. The industries may sell or buy the allowances at a cost in an emissions trading market Xu et al. (2017). The more efficient companies, whose emissions are less than their allowances, can sell excess allowances to the other companies that cannot make reductions easily. The government of Gujarat, India, recently implemented an emissions cap to restrict air pollution and permitted industries to buy/sell [†]. Therefore, CT regulation is one of the most effective market-based mechanisms for manufacturing companies to curb CE.

In a production-based supply chain, all the products are inevitably imperfect. A few of the produced items are imperfect due to factors such as production system unreliability, lack of skilled labor, weather conditions, low product quality, and others Mandal and Pal (2021). The majority of companies perform a rework process to reform the faulty products into their original versions. In some cases, imperfect products are recycled as raw materials and returned to the factory for further manufacturing. Sometimes, manufacturing companies sell imperfect products on a secondary market for a lower price.

In the recent era of the business environment, competitive actions among companies have hiked terribly. Market competition has prompted companies to enlarge sales volume to gain higher revenue and profit. The companies introduced several strategies, knowing the rivals' weaknesses to survive in

[*] https://corporate.delltechnologies.com/en-in/social-impact/advancing-sustainability/sustainable-supply-chain/environment.htm

[†] https://indianexpress.com/article/business/in-a-first-gujarat-to-launch-trading-system-with-incentive-for-low-polluting-industries-5767563/

the competitive market. In this regard, some manufacturers hired green technology (GT) to produce low-carbon products. The manufacturers/retailers also offered extended product warranty with a return/refund policy for the non-functioning product, while others designed proper strategies on selling price, product quality, and promotional effort (PE) to beat rivals Bai et al. (2019). Therefore, the supply chain model (SCnM), based on chain members' rivalry, has become very interesting to researchers.

Nowadays, product recycling has captured extreme attention from firms/industries due to shortages of resources and environmental problems Ranjbar et al. (2020). In the recycling process, collected used products are processed to manufacture new products at a lower production cost. Moreover, recycling alleviates environmental issues that originate from wastes/landfills in the environment. HP recycled 17000000 pounds of ocean-bound plastics to produce new HP products, viz., ink cartridges, monitors, laptops, etc. *HP Elite Dragonfly* is the first notebook manufactured by HP with ocean-bound plastic materials[‡]. Recycling used products is a fruitful tactic to reduce emission levels and manufacturing costs. Therefore, product recycling in the SCnM has become a fascinating area in current research.

The number of environmentally conscious customers is significantly increasing day after day. Customers' environmental awareness (EA) trends instigated firms/industries to modify basic production game plans Heydari et al. (2021). Regarding awareness, manufacturers exhibit an eager interest in low-carbon products. In a practical situation, complete recovery of used and waste products is nearly impossible; only a portion of the used product can be recovered. The rest is damaged, diminishing chain efficiency and negatively impacting the environment. To increase product recovery (PR) and protect the environment, chain members consider several positive measures such as green activities, promoting environment-related issues, spreading awareness about the benefit of recycling, etc. Therefore, chain members have executed environmental awareness efforts (EA_e) to make a greener globe.

The proposed article investigates answers to the following questions:

- How do the strategies on the greening level, retail price (RP), and PE instigate market demand? Which scenarios are beneficial to the players for individual and chain profit?
- Is GT effective in abating CE and which condition emits the minimum amount of carbon?
- How does EA_e and buy-back price influence the recovery rate, and in which structure is the highest product recovery possible?

In these regards, our article aims to extend a competitive SCnM considering carbon abatement technology and PE in product recycling under carbon cap regulation. The rival retailers compete based on the RP and PE. Accordingly, we model a closed-loop supply chain (CLSC) comprising a manufacturer, two rival retailers, and a recycler with an EA_e under a greening environment. In forward logistics, the manufacturer produces low-carbon products and satisfies the demand of retailers who fulfil green level, RP, and PE-influenced customers' demand. In reverse logistics, the recycler promotes EA and offers an attractive buy-back price to the customers to recover more used products. The recycler supplies the converted raw materials of the recovered products to the manufacturer for the following production purposes. The proposed setup could be similar to an example: Canon, India, is a renowned company that manufactures various products and sells those items through different stores. The retail stores compete against each other for product prices to increase customer demand for better profit. Moreover, Canon, India has tied up with an authorized recycler who collects e-waste such as ink cartridges, toner cartridges, camera batteries, etc., and recycles the waste in an eco-friendly process[§].

‡ https://h20195.www2.hp.com/v2/GetDocument.aspx?docname=c06614535
§ https://in.canon/en/consumer/web/e-waste

We analyze the behavior of the proposed model under a centralized and five decentralized scenarios: two manufacturer Stackelberg, retailer-recycler Stackelberg, and two Nash game structures. In each game-theoretic approach, we derive the optimal strategies of the chain members and compare the scenarios to determine which is better for individual profit. In connection to the example, Canon, India could play the Stackelberg game as a leader and find the optimal decisions to gain better individual profit. Again, retail shops and third-party recyclers could jointly participate in the Stackelberg game as leaders for higher joint profits. Moreover, the members could play the Nash game to derive optimal decisions individually for an individual profit maximization scenario.

The primary novelties of this article are summarized as follows:

- Imperfect production in closed-loop supply chain: In real-life situations, this article considers a closed-loop supply chain with an unreliable production system producing some fraction of inferior quality items. Most authors (Bai et al. (2019), Huang et al. (2020), Pang et al. (2018), Xu et al. (2017)) focused on the supply chain with the production of perfect items only. Here, we include converting the produced imperfect items into raw components for use in the subsequent production.
- Green technology investment and CT policy: We consider GT investment done by the manufacturer to curtail CE during production. Moreover, we study the SCnM under the CT policy, where the manufacturer benefits from carbon allowances. The majority of current research (Gao et al. (2018), Parsaeifar et al. (2019), Rezaei and Maihami (2020), Xu et al. (2016)) paid attention to either green technology investment or CT regulation under gas emissions environment, whereas both are taken into consideration in this article.
- Rivalry in the closed-loop supply chain: In this article, we study the competitive behaviour between retailers. The rival retailers compete against each other for the retail price and product promotion. We consider that one retailer's market demand not only depends on its selling price and product promotion but is also sensitive to that of the rival. In the existing research (Bai et al. (2019), Modak et al. (2016), Mondal and Giri (2022), Parsaeifar et al. (2019)), only retail price-based rivalry is present but, jointly, the retail price and product promotion-based rivalry are incorporated in the present study.
- Variable product recovery rate: The recycler's variable product recovery rate is designed in this research. Here, the recycler offers an attractive buy-back price and yields environmental awareness efforts to motivate customers about product recycling and to increase the quantity of recovered items. To the best of our knowledge, the buy-back price and environmental awareness effort-dependent variable recovery rate have been considered only in the study of Mandal and Pal (2023).

The rest of the present study is framed as follows: Section 3 introduces a brief survey of related past literature. Section 4 interprets the problem statement with notations and assumptions applied to construct the model. Mathematical modelling of the CLSC with variable PR rates under a CE environment is designed, and the model's behavior under different decision-making systems is analyzed in Section 5. A numerical example with some observations is posted in Subsection 5.1. Again, a sensitivity analysis is performed to check the model's efficiency, and managerial insights with implications are outlined in Subsection 5.2. Finally, concluding remarks are drawn in Section 7.

2. Literature Review

In this section, we briefly survey past research linked to our study. The current research mainly concentrates on the literature based on the following aspects: 1) supply chain with CE, green investment, and CT regulation; 2) competitive supply chain, variable market demand, and imperfect production; and 3) recycling in the supply chain.

2.1. Supply chain with carbon emissions, green investment, and cap-and-trade regulation

Adnan et al. (2023) investigated pricing decisions in two competing supply chains, each consisting of one manufacturer and one retailer with green investment in the presence of consumers' green awareness. They studied three game-theoretical approaches to derive optimal decisions of the chain. Cao et al. (2020) developed a SCnM for two firms under remanufacturing subsidy and carbon tax policies to study optimal decisions on production and pricing. They investigated the two policies and analyzed which was better for the firms. Daryanto et al. (2019) investigated the optimal delivery quantity and size in an integrated three-phase SCnM of deteriorated products with carbon emission under emission reduction incentives. Gao et al. (2018) studied a two-layer SCnM including two members: single manufacturer, single retailer (SMSR) with cooperative emission reduction strategies under a carbon tax scheme. They analyzed the model under cooperation, non-cooperation, and emission abatement cost-sharing contracts. Haijie et al. (2024) investigated a CLSC under CT regulations with a dual recycling channel. Huang et al. (2020) examined the various carbon policies in a two-tier SCnM under green investment. They assumed that CE was processed during the product's production, storage, and transportation. Jauhari et al. (2020) developed a CLSC consisting of three members with green investment under a CT policy. They constructed the model under five scenarios, including one centralized and three Stackelberg game structures. Jamali and Rasti-Barzoki (2019) proposed a sustainable SCnM for two manufacturers and a single retailer to investigate the product's pricing and greening level under a centralized system (CS) and decentralized systems (DS). They included third-party logistics between manufacturers and retailers to curtail CE and lessen delivery time. Jiang et al. (2021) formulated a two-phase SCnM comprising SMSR with emission-influenced demand under carbon reduction investment. They studied the model under the coordination of cost-sharing contracts. Jianhui et al. (2023) examined decisions on price, green level, and recycling in a CLSC under governmental subsidies. Karim and Nakade (2021) investigated the optimal decisions on green investment and production for a SCnM comprising of SMSR with product quality disruption under CE restriction. Lin et al. (2019) examined how emission regulations affect SCnM decisions in GT investment. They considered two firms and investigated their individual and optimal joint strategies under CS and DS. Liu et al. (2018) presented a SCnM in a carbon abatement environment under CT regulation. Assuming emission-influenced demand, they studied the effect of the carbon price and customers' consciousness of the environment on the chain members' optimal decisions. Pang et al. (2018) investigated a SCnM coordination mechanism with the revenue-sharing contract under CT regulation. They considered customers' EA dependent on market demand and studied the influence of EA on CE in the chain. Taleizadeh et al. (2021) modeled a CLSC model comprising a manufacturer and a distributor with a quality improvement effort and carbon reduction strategy. They applied a cost-sharing contract and analyzed the model using the Nash and Stackelberg game approaches. Taleizadeh et al. (2021) examined a dual-channel green supply chain comprising a manufacturer and a retailer under cap and trade regulation. They investigated the impact of green investment in the curtailment of CE. Wang and Song (2020) constructed a direct-retail channel SCnM under a green environment to investigate pricing policies considering the price, sales effort, and green level dependent on market demand. They examined the proposed model under CS, DS, and collaborative manners. Xu et al. (2016) presented a sustainable two-layer SCnM considering CE under CT regulation with a coordination mechanism. They included sustainability level and selling price-influenced product demand and showed how emission trading price impacts the model's optimal strategies. Xu et al. (2019) constructed an SCnM to highlight pricing and emission-abating behaviour with environmental awareness to conscious customers about carbon emission under four different governmental subsidy strategies.

2.2. *Competitive supply chain, variable market demand, and imperfect production*

Dolai et al. (2023) developed an imperfect production-based inventory model for green products under an advertisement-sensitive credit period. In their model, they considered variable screening rates sensitive to the learning effect of the workers and the number of cycles. Fadavi et al. (2022) studied a green supply chain consisting of two players, a manufacturer and a retailer, in a competitive environment. The players compete with each other for green and price-sensitive markets. Hosseini-Motlagh et al. (2021) presented a supply chain coordination problem for a manufacturer and two rival retailers with CE. Competition among retailers took place due to greening efforts. They analyzed the model under centralized, decentralized, and compensation-based contracts. Huang et al. (2016) studied a two-phase SCnM consisting of three players, viz., duopoly retailers and a manufacturer with pricing competition between the retailers. They analyzed the behaviour of chain members under six DS. Jafari et al. (2016) presented a SCnM under a dual-channel structure with a monopoly manufacturer and duopoly retailers. Their model analyzed pricing strategies for Collusion, Bertrand, and Stackelberg game approaches. Li et al. (2016) proposed a SCnM of green products under the pricing competition between the direct and retail channels. They investigated greening and pricing decisions under CS and DS. Mandal and Pal (2021) examined an imperfect production-based supply chain under a competitive trade credit financing environment. Considering selling price and PE-based rivalry between retailers, they analyzed the model under centralized and various decentralized game structures. Mondal and Giri (2020) constructed a two-period CLSCnM consisting of SMSR under a greening environment. They employed green level, marketing effort, and selling price-sensitive market demand in their model. Mondal and Giri (2022) examined a closed-loop green SCnM with retailers' competition and collection of used products under a carbon cap scheme. Their research included selling price and green level-sensitive linear demand patterns and analyzed the model under a CS and DS. Pal et al. (2015) investigated the optimal selling price and PE to maximize the profit of a two-echelon competitive SCnM by analyzing different coordination mechanisms. Pal et al. (2016) modelled a two-phase SCnM, including a supplier and two rival retailers, under a trade credit policy. Their study considered how selling price and credit period influenced competitive market demand and examined the model under integrated and Vertical Nash scenarios. Pal and Sarkar (2022) formulated a dual-channel competitive supply chain for two players under green investment. They analyzed the model using different decentralized structures from the Stackelberg and Nash games. Pal et al. (2021) constructed an imperfect production-based two-phase SCnM for deteriorated items under credit policy. They considered variable demand to be sensitive to product quality and promotional level. Panja et al. (2023) designed a joint offline and online retailer business by proposing a utility-based approach to reflect the choosing behaviour of the customers over the available alternatives. Parsaeifar et al. (2019) proposed a multi-product three-phase SCnM comprising one manufacturer, multiple suppliers, and retailers under the competition among the chain players with recycling of products. They assumed that RP and product greenness are variable linear demands of retailers.

2.3. Recycling in supply chain

Asghari et al. (2022) studied a green CLSCnM consisting of a green manufacturer, a retailer, and a collector. They considered retail price and environmental efforts sensitive to variable market demand and analyzed the model under different decentralized scenarios. Behrooz et al. (2023) constructed a dual-channel CLSC with product recycling under a greening environment. Cao et al. (2022) investigated a CLSC with remanufacturing and product recycling. They considered various alliances: the original manufacturer, the remanufacturer, and the third-party recycling platform. Jiang and Zheng (2023) explored the pricing and remanufacturing decisions of two firms with product recycling in the presence of consumers' EA. The outcomes showed that firms trade between collection cost and profit when EA gets lower. A CLSCnM of duopolies retailers and one manufacturer was constructed by Modak et al. (2016) with product recycling. They considered sales price and recycling factors depending on end-customer demand and compared the Collusion and Cournot games model. Pal and Sarkar (2021) investigated a dual-channel supply chain in a green environment with product promotion and recycling of used items. Rezaei and Maihami (2020) modelled a multi-echelon SCnM comprising SMSR and a collector remanufacturing of collected products under carbon abatement strategies. They studied the model under Stackelberg, Nash game, and DS's bargaining structures and compared the resulting decentralized approaches with a CS. A CLSCnM with the returned product's remanufacturing under a technology license was formulated by Taleizadeh et al. (2019). They included technology investment under the CT policy to curtail CE and considered price, emission reduction, and quality effort-sensitive market demand. Tsao et al. (2018) designed a two-phase SCnM considering CE and remanufacturing returned products. After minimizing the network cost in the forward channel, they investigated remanufacturing centers' optimal replenishment cycle, number, and service areas. Wang and Wu (2020) investigated emission reduction and product collection strategies in a CLSCnM under the CT policy and explored the model under CS and DS. Wei et al. (2021) examined the effect of retailing and collecting channels strategies on optimal decisions and profit in a three-layer CLSC under a competitive collection environment. Zhang et al. (2020) designed a dual-channel CLSCnM to recycle inferior quality and waste products. They investigated pricing and quality decisions and proposed a sharing contract on revenue to stimulate retailers towards the collection of used products.

2.4. Research gaps and contributions

The contribution of the current work concerning other closely related research is summarized in Tables 1 and 2. The following primary research gaps and contributions are introduced based on the existing literature connected to a CLSC system with variable recovery rates.

1. Several previous studies (Bai et al. (2019), Huang et al. (2020), Pang et al. (2018), Xu et al. (2017)) mainly focused on producing perfect quality items only. Here, we consider imperfect production by converting imperfect goods to raw materials for subsequent production.
2. Only a few researchers (Gao et al. (2018), Parsaeifar et al. (2019), Rezaei and Maihami (2020), Xu

et al. (2016)) paid attention to one or two factors amongst carbon generation, green investment, and CT regulation, but we present the trio concurrently in the current study.
3. The RP-based rivalry usually exists in past literature (Bai et al. (2019), Modak et al. (2016), Mondal and Giri (2022), Parsaeifar et al. (2019)); however, RP and PE-based competition are jointly present in our article.
4. We assume GT level, RPs, and PEs sensitive linear market demand patterns, whereas it was absent in a more significant segment of former research (Jauhari et al. (2020), Rezaei and Maihami (2020), Taleizadeh et al. (2019), Wang and Wu (2020)).
5. As far as our knowledge, only the research of Mandal and Pal (2023) has considered the buy-back price and EA-influenced variable recovery rate of the used product under the environment discussed above.

Addressing the research gaps to conduct research, we explore a SCnM problem under the following aspects. 1. Construction of a CLSC, including one manufacturer and two rival retailers with used PR by a recycler. 2. Study of the emission abatement technology under CT regulation. 3. Investigation of the rivalry among the retailers on RPs and PEs. 4. Incorporation of a market demand influenced by RPs, retailers' PEs, and the manufacturer's green innovation level. 5. Introducing the buy-back price and EA_e-dependent PR rate.
Table 1 and 2 illustrate a brief comparative review of the present research with the existing literature.

Table 1. A brief summary of the literature review corresponding to chain description.

Authors	Supply chain description							
	Members	Recycling	IP	CE	GI	CT	EA	CPE
Bai et al. (2019)	manufacturer, two retailers	×	×	√	√	√	×	√
Gao et al. (2018)	manufacturer, retailer	×	×	√	√	×	×	×
Heydari et al. (2021)	manufacturer, retailer	×	×	√	√	×	√	×
Huang et al. (2020)	supplier, retailer	×	×	√	√	√	×	×
Jauhari et al. (2020)	manufacturer, retailer, collecter	√	√	√	√	√	×	×
Modak et al. (2016)	manufacturer, duo-poly retailers	√	×	×	×	×	×	√
Mondal and Giri (2022)	manufacturer, two retailers	√	×	√	√	√	×	√
Pang et al. (2018)	manufacturer, retailer	×	×	√	√	√	√	×

Parsaeifar et al. (2019)	manufacturer, multiple suppliers, retailer	√	×	×	√	×	×	√
Rezaei and Maihami (2020)	manufacturer, collector, retailer	√	×	√	×	×	×	√
Taleizadeh et al. (2019)	manufacturer, distributor, collector	√	√	√	√	√	×	×
Wang and Song (2020)	manufacturer, retailer	×	×	×	√	×	×	×
Wang and Wu (2020)	manufacturer, retailer, third party	√	×	√	×	√	×	×
Xu et al. (2016)	manufacturer, supplier	×	×	√	×	√	×	×
Xu et al. (2017)	manufacturer, retailer	×	×	√	√	√	√	×
Our work	manufacturer, two retailers, recycler	√	√	√	√	√	√	√

IE: Imperfect production, CE: Carbon emissions, GI: Green investment, CT: Cap-and-trade policy, EA: Environmental awareness, CPE: Competitive environment

Table 2. A brief summary of the related literature corresponding to demand pattern, decision variables, and product recovery.

Authors	Market demand depends on			Recovery rate sensitive to		Decision variables
	GL [¶]	Retail price	PE[‖]/ AF[‡‡]	EAE [**]	BP [††]	
Bai et al. (2019)	√	√	×	×	×	selling prices of the retailers, green technology level
Gao et al. (2018)	×	√	×	×	×	wholesale price, retail price, emission reduction
Heydari et al. (2021)	√	√	×	×	×	selling price, green quality
Huang et al. (2020)	×	×	×	×	×	transportation lot size, no. of shipments, green investment
Jauhari et al. (2020)	√	√	×	×	×	green technology level, quality level, wholesale price, selling price, collection rate
Modak et al. (2016)	×	√	×	×	×	retail prices, recycling factors
Mondal and Giri (2022)	√	√	×	×	×	greening level, retail prices, wholesale prices
Pang et al. (2018)	×	×	×	×	×	order quantity, carbon emission
Parsaeifar et al. (2019)	√	√	×	×	×	wholesale price, green degree, raw material price, total raw materials
Rezaei and Maihami (2020)	×	√	×	×	×	wholesale price, carbon emission reduction rate, selling price

¶ Green technology level
‖ Promotional effort
** Environmental awareness effort
†† Buy-back price
‡‡ advertisement frequency

Taleizadeh et al. (2019)	×	√	×	×	×	carbon emission reduction rate, quality effort, distributor's inventory level, compensated price of return product
Wang and Song (2020)	√	√	√	×	×	green level, sales effort, selling price
Wang and Wu (2020)	×	√	×	×	×	wholesale price, return rate, emission abatement level, retail price
Xu et al. (2016)	×	√	×	×	×	sustainability level, selling price
Xu et al. (2017)	×	×	×	×	×	eco-friendly level of product, product quantity
Our work	√	√	√	√	√	green technology level, retail prices, promotional efforts, buy-back price, EA_e

3. Problem description

A multi-layer SCnM consisting of a manufacturer, two rival retailers, and a single recycler is considered with recycling of used products in the presence of green investment and EA_e under the CT policy. In forward logistics, the manufacturer produces green products with CE reduction incentives and wholesales the products to rival retailers. Here, some percentage of manufactured products are faulty due to the production system's unreliability. The ith retailer directly satisfies the end customer demand that is influenced by green innovation, RPs, and PEs. In backward logistics, the recycler collects used products from the end customers at an attractive buy-back price. The collected products go through an inspection process and are separated into two parts: in the first part, recyclable items are converted into raw components and delivered to the manufacturer; in the second part are disposable/landfill items.

The manufacturing system produces some faulty products due to labour and weather issues, deterioration of machine equipment, and a wide range of other controllable and uncontrollable factors (Pal et al. (2021)). The manufacturer spends money converting imperfect goods into raw materials that are reused for production in the future. Moreover, the manufacturer invests in GT to curtail CE during production under the CT policy (Bai et al. (2019)). Under the CT regulation, the government agency assigns firms specific carbon emission quotas (Xu et al. (2017)). An emission penalty is imposed against a firm that exceeds the pre-determined limit. In the chain, the competitive behavior between the retailers is investigated (Mandal and Pal (2021)). The retailers compete against each other for retail price and PE. Here, one retailer's demand is assumed to be dependent not only on its own retail price and PE but also on the rival's. The recycler recovers the used items from the customers for the purpose of recycling (Pal and Sarkar (2021)). The recycler offers attractive buy-back prices and promotes EA efforts to increase used product collection. Figure 1 indicates the graphical view of the problem.

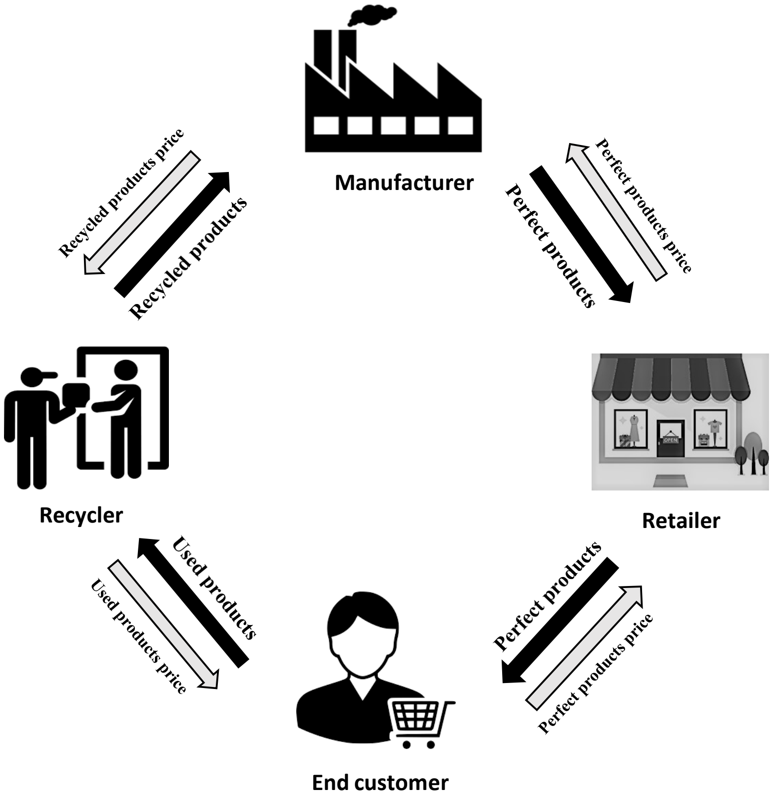


Figure 1. Pictorial view of the problem.

3.1. Notations

Throughout the article, the following notations are presented.

Decision variables:	
Manufacturer:	
g	Green technology level.
s_{mi}	Wholesale price of the manufacturer to the ith retailer (\$/unit).
Retailers:	
s_{ri}	ith retailer's selling price (\$/unit), $i = 1, 2$.
ρ_i	ith retailer's promotional effort level, $i = 1, 2$.
Recycler:	
p_b	Buy-back price of used product (\$/unit).
ψ	Recycler's environmental awareness effort level.
Input parameters:	
Manufacturer:	
C_{ms}	Raw component cost paid to the supplier by the manufacturer (\$/unit).
C_{mc}	Raw component cost paid to the re-cycler by the manufacturer (\$/unit).
C_{co}	Conversion cost of raw component from the imperfect items (\$/unit).
α	Fraction of imperfect items production, $0 < \alpha < 1$.
C_e	Carbon emissions cost (\$/kg).
C	Permitted carbon emissions limit (kg/unit time).
a	Carbon emissions in the production time without green investment (kg/unit).
b	Green technology effect parameter to reduce carbon emissions in the production time.
β	Green technology investment cost coefficient.
Retailers:	
κ_1	Promotional effort cost coefficient of the first retailer.
κ_1	Promotional effort cost coefficient of the second retailer.
Recycler:	
C_s	Recycling (inspection and converting) cost of the recovered product (\$/unit).
R_r	Recovery rate of used product (unit/unit time).
x	Fraction of raw materials converted from collected products, $0 < x < 1$.
l	Environmental awareness effort cost coefficient.
Dependent variables:	
D_i	End customer demand rate to the ith retailer (unit/unit time).
Π_M	Manufacturer's profit function.
Π_{Ri}	ith retailers' profit function.
Π_{RC}	Recycler's profit function.

3.2. Assumptions

The following assumptions are made to construct the model.

Assumption 1: The production system is unreliable; it produces some fraction of imperfect quality items, and upon bearing the cost of C_{co} per unit, the items are converted into raw components.

Assumption 2: To curb CE and to increase product demand, the manufacturer invests in green innovation technology with associated unit cost $\frac{1}{2}\beta g^2$, where g is the green innovation level, and $\beta(>0)$ is the investment cost coefficient. Similar to Bai et al. (2019), the cost function is taken in quadratic form.

Assumption 3: In the production time, CE per unit item is $(a - bg)$. Here, we assume $0 \leq g < \frac{a}{b}$ to avoid negative emission. Greater values of g imply lower CE. Bai et al. (2019)

Assumption 4: The rival retailers compete against each other for RP and product promotion. Here, one retailer's market demand depends on his and the other's RP and PE. Therefore, green innovation level, RP, and PE-sensitive end customers' linear demand pattern is considered and presented as:
$D_i(g, p_i, \rho_i) = \gamma_i + \delta_i g - \zeta_i s_{ri} + \eta_i s_{rj} + \lambda_i \rho_i - \mu_i \rho_j, \;\; i, j = 1, 2$ and $i \neq j$, where $\gamma_i(>0)$ is the base market, $\delta_i(>0)$ measures the elasticity of demand regarding green innovation level, $\zeta_i(>0)$ measures the impact of RP on demand by the retailers, $\eta_i(>0)$ measures the effect of rival's RP on demand, $\lambda_i(>0)$ measures the influence of promotion on demand by the retailers, and $\mu_i(>0)$ measures the effect of rival's promotion on demand. Here, $\zeta_i > \eta_i$ and $\lambda_i > \mu_i$, as one retailer's demand is more sensitive to their RP and PE than the rival's Bai et al. (2019). To overcome mathematical complexity, we take the demand function as $D_i(g, p_i, \rho_i) = \gamma_i + \delta g - \zeta s_{ri} + \eta s_{rj} + \lambda \rho_i - \mu \rho_j, \;\; i, j = 1, 2$ and $i \neq j$.
We consider that the end customers' demand for the individual retailer and each retailer's demand for the manufacturer are equal.

Assumption 5: The ith retailer spends per unit promotional cost $\frac{1}{2}\kappa_i \rho_i^2$ for promotion of product to increase market demand, where ρ_i is the PE level and $\kappa_i(>0)$ is the promotional cost coefficient.

Assumption 6: The recycler recovers the used products from the end customers at a rate R_r. To motivate customers to recycle and to increase PR, the recycler offers the best buy-back price and promotes EA. As rising values of buy-back price and EA_e positively impact product collection, the recovery rate is taken in the form: $R_r = h(p_b + \psi)$. Moreover, the recycler expends cost $\frac{1}{2}l\psi^2$ for EA_e to uprise PR, where ψ is the awareness effort level and $l > 0$ is the cost coefficient.

4. Mathematical modeling

In this CLSCnM, the manufacturing system generates perfect and imperfect quality products together. After receiving the manufacturer's environment-friendly perfect items, both retailers directly sell those items to the end customers. The system acquires perfect items at a rate (1-α) times the production rate, where $0 < \alpha < 1$. The manufacturer funds GT, observing the end customers' tendency toward a green product. The manufacturer adopts the CT policy to control CE during production. From a rival's perspective, each retailer has the following options for sales increment: offering a lower selling price, extending PE, or applying both together. The recycler supervises the buy-back price of used products and the EA_e level to increase EA among customers and acquire a good collection of used products. The collected products are inspected by the recycler and categorized into two parts. Figure 2 illustrates the supply chain workflow.

4.1. Manufacturer's model

The manufacturing system manufactures products at $(D_1 + D_2)/(1 - \alpha)$, whereas the imperfect items are generated at α times the production rate. The faulty items are converted to raw components by the manufacturer for the next production. For production, the manufacturer accumulates raw materials/components from three sources, viz., supplier, self, and recycler. The manufacturer funds green innovation technology to meet end customers' need for greener products and curb CE. Meanwhile, by controlling emissions, the manufacturer obeys the CT regulation for a less polluted environment.

The manufacturer receives $xR_r(D_1 + D_2)$ units recycled raw components per unit time from the recycler for production. Therefore, raw materials cost paid to recycler is $C_{mc}\ xR_r(D_1 + D_2)$. Again, $\alpha\frac{D_1+D_2}{1-\alpha}$ units imperfect items are converted to raw components. So, converted raw materials cost is $C_{co}\ \alpha\frac{D_1+D_2}{1-\alpha}$. Supplier settles the remaining raw materials' requirement, hence raw components cost paid to supplier is $C_{ms}\left[\frac{D_1+D_2}{1-\alpha} - xR_r(D_1 + D_2) - \alpha\frac{D_1+D_2}{1-\alpha}\right]$. The CE amount for the production of $\frac{D_1+D_2}{1-\alpha}$ units item is $(a - bg)\frac{D_1+D_2}{1-\alpha}$. Therefore, CE cost is $\left[C_e(a - bg)\frac{D_1+D_2}{1-\alpha} - C\right]$ and the associated GT cost is $\frac{1}{2}\frac{D_1+D_2}{1-\alpha}\beta g^2$. Sales revenue collected by the manufacturer from the two retailers is $s_{m1}D_1 + s_{m2}D_2$.

The manufacturer's profit is denoted by Π_M and presented as:

$$
\begin{aligned}
\Pi_M &= \text{Collected sales revenue - All predefined cost} \\
&= \text{Sales revenue collected from the two retailers - raw materials cost paid to recycler} \\
&\quad \text{- converted raw materials cost - raw components cost paid to supplier - CE cost - GT cost} \\
&=(s_{m1}D_1 + s_{m2}D_2) - C_{mc}\ xR_r(D_1 + D_2) - C_{co}\ \alpha\frac{D_1 + D_2}{1-\alpha} \\
&\quad - C_{ms}\left[\frac{D_1 + D_2}{1-\alpha} - xR_r(D_1 + D_2) - \alpha\frac{D_1 + D_2}{1-\alpha}\right] - \left[C_e(a - bg)\frac{D_1 + D_2}{1-\alpha} - C\right] - \frac{1}{2}\frac{D_1 + D_2}{1-\alpha}\beta g^2
\end{aligned} \tag{1}
$$

4.2. *Retailers' model*

The end customers' demand for the retailers is influenced by each retailer's RP and PE, which proves the rivalry between the retailers. To survive in a rivalry environment, individual retailers desire to curtail the RP and augment the PE compared with rivals.

The ith retailer's buying price is $s_{mi}D_i$. Promotional cost for the ith retailer is $\frac{1}{2}D_i\kappa_i\rho_i^2$. Earned sales revenue of the ith retailer is $s_{ri}D_i$.
The underneath equation defines the ith retailer's profit.

$$\Pi_{Ri} = \text{Sales revenue - Promotional cost}$$

$$\text{i.e., } \Pi_{Ri} = s_{ri}D_i - s_{mi}D_i - \frac{1}{2}D_i\kappa_i\rho_i^2, \quad i = 1, 2 \tag{2}$$

4.3. *Recycler's model*

The recycler's target is to collect as many used products from customers as possible. For this, the recycler offers the best buy-back price and awakens the public toward the environmental benefit of recycling. The gathered used products are inspected and divided into two parts. The first part is recyclable items to be converted into raw materials; the other is disposable/landfilled items. Only the x fraction of collected products are converted into raw components and delivered to the manufacturer for the next production.

Buy-back cost of the recycler is $p_bR_r(D_1 + D_2)$. Recycler's EA_e cost is $\frac{1}{2}l\psi^2$. Recycler's product recyling (inspection and converting) cost is $C_sR_r(D_1 + D_2)$. Recycler's collected revenue from the manufacturer for delivering raw materials is $C_{mc}xR_r(D_1 + D_2)$.

The expression of the recycler's profit is given in the below equation.

$$\Pi_{RC} = \text{Collected revenue - Buy-back cost - Inspection cost}$$
$$- \text{Environmental awareness effort cost}$$
$$= C_{mc}xR_r(D_1 + D_2) - p_bR_r(D_1 + D_2) - C_sR_r(D_1 + D_2) - \frac{1}{2}l\psi^2 \tag{3}$$

Now, the following game theoretic models are considered:

- Centralized system (CS)
- Manufacturer-Stackelberg model 1 (MS1)
- Manufacturer-Stackelberg model 2 (MS2)
- Retailer-recycler Stackelberg model (RCS)
- Vertical Nash model 1 (VN1)
- Vertical Nash model 2 (VN2)

The determination of optimal decisions and, consequently, the profits of each player are discussed under all the game-theoretic approaches mentioned above.

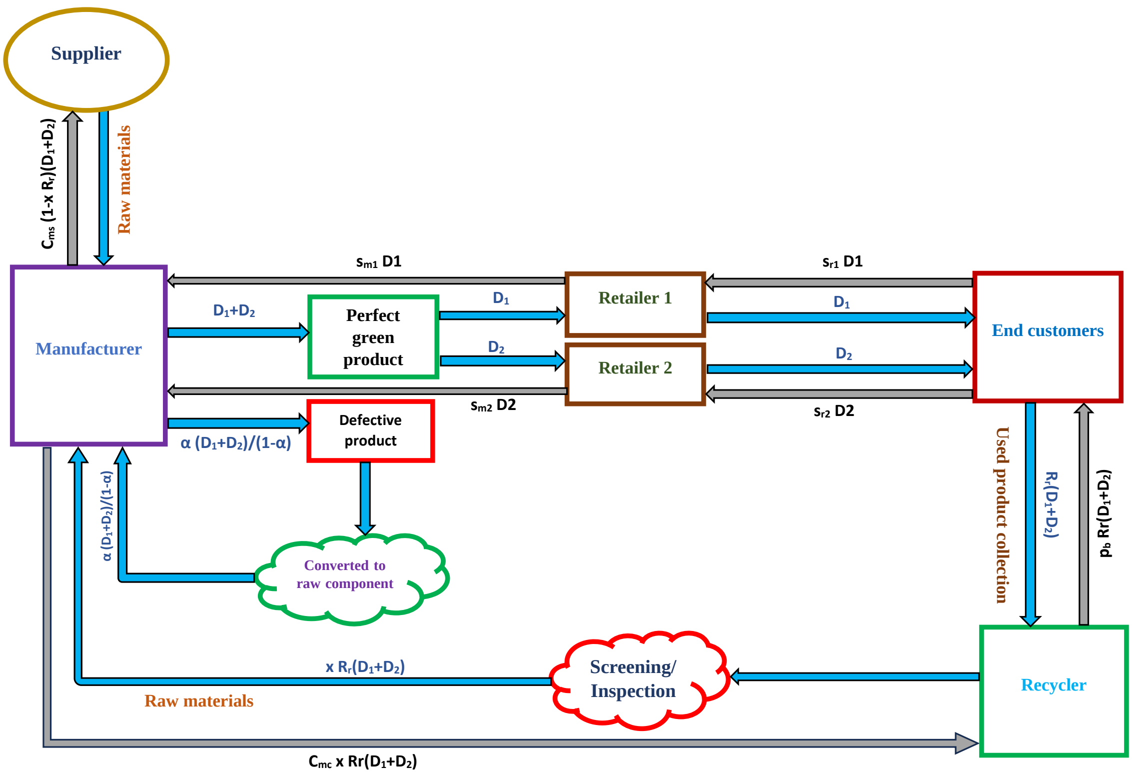


Figure 2. Workflow of the model.

4.4. Centralized system (CS)

In the CS, the manufacturer, the retailers, and the recycler act as a team, and one centralized decision is taken to optimize the integrated profit of the chain. Here, the manufacturer makes a contract with the recycler in which the manufacturer will pay a fixed raw component cost to the recycler. Moreover, the manufacturer offers a deal to the retailers based on their selling prices, where $s_{m1} = z_1 s_{r1}$ and $s_{m2} = z_2 s_{r2}$, $z_1 \gtreqless z_2$, whenever $s_{r1} \gtreqless s_{r2}$ and $0 < z_1 < 1$, $0 < z_1 < 1$.

The integrated profit of the chain,

$$\Pi^{CS}(g, s_{ri}, \rho_i, p_b, \psi) = \Pi_M + \sum_{i=1}^{2} \Pi_{Ri} + \Pi_{RC} \tag{4}$$

Now, the problem is to
Maximize $\Pi^{CS}(g, s_{ri}, \rho_i, p_b, \psi)$ subject to the constraints $\frac{a}{b} > g > 0$, $s_{ri} > 0$, $\rho_i > 0$, $p_b > 0$, $0 < (\psi + p_b) < \frac{1}{h}$.

Solution procedure: To optimize the profit function $\Pi^{CS}(g, s_{ri}, \rho_i, p_b, \psi)$, we derive the partial derivatives of $\Pi^{CS}(g, s_{ri}, \rho_i, p_b, \psi)$ concerning the decision variables up to second-order. Equating first-order derivatives equal to zero, the values of g, s_{ri}, ρ_i, p_b, and ψ are determined. These values are optimal, i.e., $g = g^*$, $s_{ri} = s^*_{ri}, \rho_i = \rho^*_i$, $p_b = p^*_b$, and $\psi = \psi^*$ if the Hessian matrix (HN_m) corresponding to the profit function is negative definite, i.e., all eigenvalues of the HN_m are negative. Where,

$$H^{CS} = \begin{pmatrix}
\frac{\partial^2\Pi^{CS}}{\partial g^2} & \frac{\partial^2\Pi^{CS}}{\partial g \partial s_{r1}} & \frac{\partial^2\Pi^{CS1}}{\partial g \partial s_{r2}} & \frac{\partial^2\Pi^{CS}}{\partial g \partial \rho_1} & \frac{\partial^2\Pi^{CS}}{\partial g \partial \rho_2} & \frac{\partial^2\Pi^{CS}}{\partial g \partial p_b} & \frac{\partial^2\Pi^{CS}}{\partial g \partial \psi} \\
\frac{\partial^2\Pi^{CS}}{\partial s_{r1} \partial g} & \frac{\partial^2\Pi^{CS}}{\partial s_{r1}^2} & \frac{\partial^2\Pi^{CS}}{\partial s_{r1} \partial s_{r2}} & \frac{\partial^2\Pi^{CS}}{\partial s_{r1} \partial \rho_1} & \frac{\partial^2\Pi^{CS}}{\partial s_{r1} \partial \rho_2} & \frac{\partial^2\Pi^{CS}}{\partial s_{r1} \partial p_b} & \frac{\partial^2\Pi^{CS}}{\partial s_{r1} \partial \psi} \\
\frac{\partial^2\Pi^{CS}}{\partial s_{r2} \partial g} & \frac{\partial^2\Pi^{CS}}{\partial s_{r2} \partial s_{r1}} & \frac{\partial^2\Pi^{CS}}{\partial s_{r2}^2} & \frac{\partial^2\Pi^{CS}}{\partial s_{r2} \partial \rho_1} & \frac{\partial^2\Pi^{CS}}{\partial s_{r2} \partial \rho_2} & \frac{\partial^2\Pi^{CS}}{\partial s_{r2} \partial p_b} & \frac{\partial^2\Pi^{CS}}{\partial s_{r2} \partial \psi} \\
\frac{\partial^2\Pi^{CS}}{\partial \rho_1 \partial g} & \frac{\partial^2\Pi^{CS}}{\partial \rho_1 \partial s_{r1}} & \frac{\partial^2\Pi^{CS}}{\partial \rho_1 \partial s_{r2}} & \frac{\partial^2\Pi^{CS}}{\partial \rho_1^2} & \frac{\partial^2\Pi^{CS}}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2\Pi^{CS}}{\partial \rho_1 \partial p_b} & \frac{\partial^2\Pi^{CS}}{\partial \rho_1 \partial \psi} \\
\frac{\partial^2\Pi^{CS}}{\partial \rho_2 \partial g} & \frac{\partial^2\Pi^{CS}}{\partial \rho_2 \partial s_{r1}} & \frac{\partial^2\Pi^{CS}}{\partial \rho_2 \partial s_{r2}} & \frac{\partial^2\Pi^{CS}}{\partial \rho_2 \partial \rho_1} & \frac{\partial^2\Pi^{CS}}{\partial \rho_2^2} & \frac{\partial^2\Pi^{CS}}{\partial \rho_2 \partial p_b} & \frac{\partial^2\Pi^{CS}}{\partial \rho_2 \partial \psi} \\
\frac{\partial^2\Pi^{CS}}{\partial p_b \partial g} & \frac{\partial^2\Pi^{CS}}{\partial p_b \partial s_{r1}} & \frac{\partial^2\Pi^{CS}}{\partial p_b \partial s_{r2}} & \frac{\partial^2\Pi^{CS}}{\partial p_b \partial \rho_1} & \frac{\partial^2\Pi^{CS}}{\partial p_b \partial \rho_2} & \frac{\partial^2\Pi^{CS}}{\partial p_b^2} & \frac{\partial^2\Pi^{CS}}{\partial p_b \partial \psi} \\
\frac{\partial^2\Pi^{CS}}{\partial \psi \partial g} & \frac{\partial^2\Pi^{CS}}{\partial \psi \partial s_{r1}} & \frac{\partial^2\Pi^{CS}}{\partial \psi \partial s_{r2}} & \frac{\partial^2\Pi^{CS}}{\partial \psi \partial \rho_1} & \frac{\partial^2\Pi^{CS}}{\partial \psi \partial \rho_2} & \frac{\partial^2\Pi^{CS}}{\partial \psi \partial p_b} & \frac{\partial^2\Pi^{CS}}{\partial \psi^2}
\end{pmatrix}_{(g^*,\, s^*_{r1},\, s^*_{r2},\, \rho^*_1,\, \rho^*_2,\, p^*_b,\, \psi^*)}$$

As all the second-order partial derivatives of $\Pi^{CS}(g, s_{ri}, \rho_i, p_b, \psi)$ are complicated, it is tough enough to find an analytical solution to the problem. We numerically test the above optimality condition using the well-known computer software Mathematica 11.1.1.

4.5. Decentralized system (DS)

In DS, individual players can make their own decisions. Here, we undergo three Stackelberg and two Nash structures. In the Stackelberg approach, a game is played alternatively among the chain members by the leader-follower rule, where one member is the leader, and the rest are followers.

4.5.1. Manufacturer-Stackelberg (MS1) model 1

In the Stackelberg game, all the supply chain members optimize their corresponding decisions sequentially according to the decision-making power. Here, the manufacturer leads the supply chain, and other members follow the manufacturer. According to the Stackelberg game principle, the optimal decisions of the followers are derived sequentially. Then, the leader uses the followers' findings in the profit function and derives optimal responses.

Here, the decision making power structures are:
Level 1: Manufacturer, max $\Pi^{ms1}_M(g, s_{m1}, s_{m2})$ subject to $g > 0$, $s_{m1} > s_{r1}$, and $s_{m2} > s_{r2}$

Level 2: Recycler, max $\Pi_{RC}^{ms1}(\psi, p_b)$ subject to $0 < (\psi + p_b) < \frac{1}{h}$, $p_b > 0$
Level 3: Two retailers (play individually), max $\Pi_{Ri}^{ms1}(s_{ri}, \rho_i)$ subject to $s_{ri} > 0, \rho_i > 0$
The two retailers derive optimal RPs and PEs independently to maximize their individual profits. Knowing the retailers' strategies, the recycler optimizes its own profit for the decision on ψ and p_b. Meanwhile, observing the reactions on ψ, p_b of the recycler and s_{ri}, and ρ_i of the retailers, the manufacturer finds out the optimal decision on g, s_{m1}, and s_{m2} to maximize own profit.

Now, individual profit of the ith retailer, $\Pi_{Ri}^{ms1} = \Pi_{Ri}, i = 1, 2$ (5)

The objective of the ith retailer is to Maximize Π_{Ri}^{ms1} subject to $s_{ri} > 0, \rho_i > 0$.

Proposition 4.1. $\Pi_{Ri}^{ms1}(s_{ri}, \rho_i)$ *takes maximum value at* $(s_{ri}^{ms1}, \rho_i^{ms1})$ *if the condition* $2\zeta k_i - \lambda^2 > 0$ *holds.*

Proof. See the Appendix A

Now, replacing s_{r1}, s_{r2}, ρ_1, and ρ_2 by s_{r1}^{ms1}, s_{r1}^{ms1}, ρ_1^{ms1}, and ρ_2^{ms1}, respectively, we get profit of the recycler,

$$\Pi_{RC}^{ms1}(\psi, p_b) = C_{mc}xR_r(D_1' + D_2') - p_bR_r(D_1' + D_2') - C_sR_r(D_1' + D_2') - \frac{1}{2}l\psi^2 \tag{6}$$

where D_1' and D_1' are obtained by substituting s_{r1}^{ms1}, s_{r1}^{ms1}, ρ_1^{ms1}, and ρ_2^{ms1} in D_1 and D_2.
The target of the recycler is to Maximize $\Pi_{RC}^{ms1}(\psi, p_b)$ subject to $0 < (\psi + p_b) < \frac{1}{h}$, $p_b > 0$

Proposition 4.2. $\Pi_{RC}^{ms1}(\psi, p_b)$ *takes maximum value at* $\psi^{ms1} = \frac{h(C_s - xC_{mc})(D_1' + D_2')}{h(D_1' + D_2') - 2l}$, $p_b^{ms1} = \frac{(C_s - xC_{mc})(hD_1' + hD_2' - l)}{h(D_1' + D_2') - 2l}$ *if the condition* $2l > h(D_1' + D_2')$ *holds.*

Proof. See the Appendix B

Knowing the responses of the retailers and recycler, the manufacturer takes decisions on g and s_{mi}. Substituting the values of ψ^{ms1} and p_b^{ms1} and then replacing s_{r1}^{ms1}, s_{r2}^{ms1}, ρ_1^{ms1}, and ρ_2^{ms1} in equation (1), we get the profit of the manufacturer as

$$\begin{aligned}
&\Pi_M^{ms1}(g, s_{m1}, s_{m2})\\
&=\Big(s_{m1}D_1(g, s_{r1}^{ms1}, s_{r2}^{ms1}, \rho_1^{ms1}, \rho_2^{ms1}) + s_{m2}D_2(g, s_{r1}^{ms1}, s_{r2}^{ms1}, \rho_1^{ms1}, \rho_2^{ms1})\Big)\\
&\quad - \Big(D_1(g, s_{r1}^{ms1}, s_{r2}^{ms1}, \rho_1^{ms1}, \rho_2^{ms1}) + D_2(g, s_{r1}^{ms1}, s_{r2}^{ms1}, \rho_1^{ms1}, \rho_2^{ms1})\Big)\\
&\quad \left[C_{mc}\, xh(p_b^{ms1} + \psi^{ms1}) + C_{ms}\left(\frac{1}{1-\alpha} - xh(p_b^{ms1} + \psi^{ms1}) - \frac{\alpha}{1-\alpha}\right)\right.\\
&\quad \left. + C_{co}\,\frac{\alpha}{1-\alpha} + \frac{C_e(a - bg)}{1-\alpha} + \frac{\beta g^2}{2(1-\alpha)}\right] + C
\end{aligned} \tag{7}$$

Now, our target is to Maximize $\Pi_M^{ms1}(g, s_{m1}, s_{m2})$ subject to $g > 0$, $s_{m1} > s_{r1}$, and $s_{m2} > s_{r2}$
Equations $\frac{\partial \Pi_M^{ms1}}{\partial g} = 0$, $\frac{\partial \Pi_M^{ms1}}{\partial s_{m1}} = 0$, and $\frac{\partial \Pi_M^{ms1}}{\partial s_{m2}} = 0$ yield values of $g = g^{ms1}$, $s_{m1} = s_{m1}^{ms1}$, and $s_{m2} = s_{m2}^{ms1}$; this will be the optimal solution if the j^{th} order leading principal minor, Δ_j of the HN_m corresponding to the profit function $\Pi_M^{ms1}(g^{ms1}, s_{m1}^{ms1}, s_{m2}^{ms1})$ take the sign $(-1)^j$, $j = 1, 2, 3$, i.e., $\Delta_1 < 0$, $\Delta_2 > 0$, and $\Delta_3 < 0$,

where

$$\Delta_1 = \left|\frac{\partial^2\Pi_M^{ms1}}{\partial g^2}\right|, \Delta_2 = \begin{vmatrix} \frac{\partial^2\Pi_M^{ms1}}{\partial g^2} & \frac{\partial^2\Pi_M^{ms1}}{\partial g\partial s_{m1}} \\ \frac{\partial^2\Pi_M^{ms1}}{\partial s_{m1}\partial g} & \frac{\partial^2\Pi_M^{ms1}}{\partial s_{m1}^2} \end{vmatrix}, \Delta_3 = \begin{vmatrix} \frac{\partial^2\Pi_M^{ms1}}{\partial g^2} & \frac{\partial^2\Pi_M^{ms1}}{\partial g\partial s_{m1}} & \frac{\partial^2\Pi_M^{ms1}}{\partial g\partial s_{m2}} \\ \frac{\partial^2\Pi_M^{ms1}}{\partial s_{m1}\partial g} & \frac{\partial^2\Pi_M^{ms1}}{\partial s_{m1}^2} & \frac{\partial^2\Pi_M^{ms1}}{\partial s_{m1}\partial s_{m2}} \\ \frac{\partial^2\Pi_M^{ms1}}{\partial s_{m2}\partial g} & \frac{\partial^2\Pi_M^{ms1}}{\partial s_{m2}\partial s_{m1}} & \frac{\partial^2\Pi_M^{ms1}}{\partial s_{m2}^2} \end{vmatrix}$$

Due to the longer expression of the manufacturer's profit function, we verify the condition numerically. Replacing g, s_{m1}, and s_{m2} by g^{ms1}, s_{m1}^{ms1}, and s_{m2}^{ms1} respectively, in equation (10), we get the manufacturer's optimum profit.

4.5.2. Manufacturer-Stackelberg (MS2) model 2

This is another case of the manufacturer Stackelberg model. In this game, the manufacturer plays the role of leader and other members are followers. Here, the two retailers play as a single member and jointly make strategies on selling prices and PEs to maximize their integrated profit.
The decision making power structures are:
Level 1: Manufacturer, max $\Pi_M^{ms2}(g, s_{m1}, s_{m2})$ subject to $g > 0$, $s_{m1} > s_{r1}$, and $s_{m2} > s_{r2}$
Level 2: Recycler, max $\Pi_{RC}^{ms2}(\psi, p_b)$ subject to $0 < (\psi + p_b) < \frac{1}{h}$, $p_b > 0$
Level 3: Two retailers (play jointly), max $\Pi_{JR}^{ms2}(s_{ri}, \rho_i)$ subject to $s_{ri} > 0, \rho_i > 0$

According to the Stackelberg game principle, the retailers jointly find out decisions on selling prices and PEs to maximize the integrated profit. Seeing the retailers' strategies, the recycler derives optimal ψ and p_b to optimize its own profit. Knowing the other members' strategies on ψ, p_b, s_{ri}, and ρ_i, the manufacturer optimizes its own profit for the decisions on g, s_{m1}, and s_{m2}.
Now, joint profit of the retailers,

$$\Pi_{JR}^{ms2}(s_{ri}, \rho_i) = \sum_{i=1}^{2}(s_{ri}D_i - s_{mi}D_i - \frac{1}{2}\kappa_i\rho_i^2) \tag{8}$$

Our objective is to Maximize $\Pi_{JR}^{ms2}(s_{ri}, \rho_i)$ subject to $s_{ri} > 0, \rho_i > 0$.

Proposition 4.3. *$\Pi_{JR}^{ms2}(s_{ri}, \rho_i)$ is concave function of s_{ri} and ρ_i if the conditions in* (13), (14), *and* (15) *are satisfied.*

Proof. See the Appendix C

Solving the equations $\frac{\partial\Pi_{JR}^{ms2}}{\partial s_{r1}} = 0$, $\frac{\partial\Pi_{JR}^{ms2}}{\partial s_{r2}} = 0$, $\frac{\partial\Pi_{JR}^{ms2}}{\partial \rho_1} = 0$, and $\frac{\partial\Pi_{JR}^{ms2}}{\partial \rho_2} = 0$, we get the optimal solution $(s_{r1}^{ms2}, s_{r2}^{ms2}, \rho_1^{ms2}, \rho_2^{ms2})$.

$$\text{Individual profit of the recycler, } \Pi_{RC}^{ms2}(\psi, p_b) = \Pi_{RC} \tag{9}$$

The target of the recycler is to Maximize $\Pi_{RC}^{ms2}(\psi, p_b)$ subject to $0 < (\psi + p_b) < \frac{1}{h}$, $p_b > 0$.
Using proposition 4.2, it can be shown that $\Pi_{RC}^{ms2}(\psi, p_b)$ takes maximum value at $\psi^{ms2} = \frac{h(C_s - xC_{mc})(D_1'' + D_2'')}{h(D_1'' + D_2'') - 2l}$, $p_b^{ms2} = \frac{(C_s - xC_{mc})(hD_1'' + hD_2'' - l)}{h(D_1'' + D_2'') - 2l}$ if the condition $2l > h(D_1'' + D_2'')$ holds, where D_1'' and D_2'' are obtained by substituting the values of $s_{r1}^{ms2}, s_{r2}^{ms2}, \rho_1^{ms2}$, and ρ_2^{ms2} in D_1 and D_2.
The manufacturer makes own strategies on g and s_{mi} knowing the responses of the rest of the members.

In equation (1), after substituting the values of ψ^{ms2}, p_b^{ms2}, we replace s_{r1}^{ms2}, s_{r2}^{ms2}, ρ_1^{ms2}, ρ_2^{ms2} and get the manufacturer's profit

$$\begin{aligned}
&\Pi_M^{ms2}(g, s_{m1}, s_{m2})\\
=&\Big(s_{m1}D_1(g, s_{r1}^{ms2}, s_{r2}^{ms2}, \rho_1^{ms2}, \rho_2^{ms2}) + s_{m2}D_2(g, s_{r1}^{ms2}, s_{r2}^{ms2}, \rho_1^{ms2}, \rho_2^{ms2})\Big)\\
&-\Big(D_1(g, s_{r1}^{ms2}, s_{r2}^{ms2}, \rho_1^{ms2}, \rho_2^{ms2}) + D_2(g, s_{r1}^{ms2}, s_{r2}^{ms2}, \rho_1^{ms2}, \rho_2^{ms2})\Big)\\
&\Bigg[C_{mc}\; xh(p_b^{ms2} + \psi^{ms2}) + C_{ms}\left(\frac{1}{1-\alpha} - xh(p_b^{ms2} + \psi^{ms2}) - \frac{\alpha}{1-\alpha}\right)\\
&+ C_{co}\,\frac{\alpha}{1-\alpha} + \frac{C_e(a-bg)}{1-\alpha} + \frac{\beta g^2}{2(1-\alpha)}\Bigg] + C
\end{aligned} \tag{10}$$

Now, our target is to Maximize $\Pi_M^{ms2}(g, s_{m1}, s_{m2})$ subject to $g > 0$, $s_{m1} > s_{r1}$ and $s_{m2} > s_{r2}$.

Solving the simultaneous equations $\frac{\partial \Pi_M^{ms2}}{\partial g} = 0$, $\frac{\partial \Pi_M^{ms2}}{\partial s_{m1}} = 0$, and $\frac{\partial \Pi_M^{ms2}}{\partial s_{m2}} = 0$, we get a solution $g = g^{ms2}$, $s_{m1} = s_{m1}^{ms2}$, and $s_{m2} = s_{m2}^{ms2}$; it will be the optimal solution if all the eigenvalues of the HN_m corresponding to the profit function $\Pi_M^{ms2}(g^{ms2}, s_{m1}^{ms2}, s_{m2}^{ms2})$ are negative. Substituting g^{ms2}, s_{m1}^{ms2}, and s_{m2}^{ms2} in equation (10), manufacturer's optimum profit is obtained.

4.5.3. Retailer Recycler-Stackelberg (RCS) model

In this game, the two retailers and the recycler unitedly play as a leader, whereas the manufacturer performs the follower's role. We consider fixed wholesale prices of the manufacturer equal to the obtained wholesale prices in the CS.

Here, the decision making power structures are:
Level 1: Retailers and recycler, max $\Pi_J^{rcs}(s_{ri}, \rho_i, \psi, p_b)$ subject to $s_{ri} > 0, \rho_i > 0, p_b > 0, 0 < (\psi + p_b) < \frac{1}{h}$
Level 2: Manufacturer, max $\Pi_M^{rcs}(g)$ subject to $g > 0$.

The manufacturer optimizes its own profit for the decision on g. Knowing the manufacturer's response, the retailers and recycler unitedly find out optimal strategies on $s_{r1}, s_{r2}, \rho_1, \rho_2, \psi$, and p_b to maximize their joint profit.

Individual profit of the manufacturer is $\Pi_M^{rcs}(g) = \Pi_M$ (11)

Now, our target is to Maximize $\Pi_M^{rcs}(g)$ subject to $g > 0$.

Proposition 4.4. *$\Pi_M^{rcs}(g)$ is concave function of g if the condition $g < \frac{1}{6\beta\delta}\Big(4bC_e\delta + \beta(-\gamma_1 - \gamma_2 + s_{r1}\zeta + s_{r2}\zeta - s_{r1}\eta - s_{r2}\eta - \lambda\rho_1 + \mu\rho_1 - \lambda\rho_2 + \mu\rho_2)\Big)$ holds.*

Proof. See the Appendix D

Solving $\frac{\partial \Pi_M^{rcs}}{\partial g} = 0$, we have the optimal value of g=g^{rcs}.
The retailers and the recycler jointly decide their optimal strategies knowing the decision of the manufacturer.
Joint profit of the retailers and the recycler is

$$\begin{aligned}
&\Pi_J^{rcs}(s_{ri}, \rho_i, \psi, p_b)\\
=&\sum_{i=1}^{2}\Big(s_{ri}D_i(g^{rcs}, s_{ri}, \rho_i, \psi, p_b) - s_{mi}D_i(g^{rcs}, s_{ri}, \rho_i, \psi, p_b)
\end{aligned}$$

$$- \frac{1}{2} D_i(g^{rcs}, s_{ri}, \rho_i, \psi, p_b)\kappa_i \rho_i^2\Big) + C_{mc} x R_r \sum_{i=1}^{2} D_i(g^{rcs}, s_{ri}, \rho_i, \psi, p_b)$$

$$- p_b R_r \sum_{i=1}^{2} D_i(g^{rcs}, s_{ri}, \rho_i, \psi, p_b) - C_s R_r \sum_{i=1}^{2} D_i(g^{rcs}, s_{ri}, \rho_i, \psi, p_b) - \frac{1}{2} l \psi^2 \quad (12)$$

The problem is to
Maximize $\Pi_J^{rcs}(s_{ri}, \rho_i, \psi, p_b)$ subject to $s_{ri} > 0, \rho_i > 0, p_b > 0, 0 < (\psi + p_b) < \frac{1}{h}$.
To obtain the optimum value of $\Pi_J^{rcs}(s_{ri}, \rho_i, \psi, p_b)$, we derive all the first and second order derivatives of the profit function with respect to s_{r1}, s_{r2}, ρ_1, and ρ_2. Solving the first order equations $\frac{\partial \Pi_J^{rcs}}{\partial s_{r1}} = 0$, $\frac{\partial \Pi_J^{rcs}}{\partial s_{r2}} = 0$, $\frac{\partial \Pi_J^{rcs}}{\partial \rho_1} = 0$, $\frac{\partial \Pi_J^{rcs}}{\partial \rho_2} = 0$, $\frac{\partial \Pi_J^{rcs}}{\partial \psi} = 0$, and $\frac{\partial \Pi_J^{rcs}}{\partial p_b} = 0$, we obtain the values $s_{r1} = s_{r1}^{rcs}$, $s_{r2} = s_{r2}^{rcs}$, $\rho_1 = \rho_1^{rcs}$, $\rho_2 = \rho_2^{rcs}$, $\psi = \psi^{rcs}$, and $p_b = p_b^{rcs}$. These values will be the optimal values if the HN_m of Π_J^{rcs} is negative definite at $(s_{r1}^{rcs}, s_{r2}^{rcs}, \rho_1^{rcs}, \rho_2^{rcs}, \psi^{rcs}, p_b^{rcs})$. Due to the complicated form of the profit function, we verify the above condition numerically by using Mathematica 11.1.1.

4.5.4. Vertical Nash (VN1) model 1

In the Nash game, the players have the same decision power and have set their respective decisions independently and simultaneously. The manufacturer's target is to acquire optimal profit for the decision on the green level, whatever others may make. Irrespective of others, each retailer finds its strategies for selling prices and PEs to optimize its profit. In contrast, the recycler plan of action includes EA_e and buy-back price to achieve maximum profit, ignoring others' plans.

To validate the Nash game in the proposed model, we assume that the manufacturer takes the decision on green level (g) only and wholesales the products to the retailers at a fixed price.

Here, the decision making power structures are:
Level 1: Manufacturer, max $\Pi_M^{vn1}(g)$ subject to $g > 0$
Level 1: Two retailers (play individually), max $\Pi_{Ri}^{vn1}(s_{ri}, \rho_i)$ subject to $s_{ri} > 0, \rho_i > 0$
Level 1: Recycler, max $\Pi_{RC}^{vn1}(\psi, p_b)$ subject to $0 < (\psi + p_b) < \frac{1}{h}$, $p_b > 0$.

Recalling propositions 4.4, 4.1, and 4.2, it can be verified that $\Pi_M^{vn1}(g)$ is concave on g, $\Pi_{R1}^{vn1}(s_{r1}, \rho_1)$ is a concave function of s_{r1} and ρ_1, and $\Pi_{R2}^{vn1}(s_{r2}, \rho_2)$ is concave on s_{r2} and ρ_2, $\Pi_{RC}^{vn1}(\psi, p_b)$ is a concave function of ψ and p_b.

Therefore, solving the simultaneous equations $\frac{\partial \Pi_M^{vn1}}{\partial g} = 0$, $\frac{\partial \Pi_{R1}^{vn1}}{\partial s_{r1}} = 0$, $\frac{\partial \Pi_{R1}^{vn1}}{\partial \rho_1} = 0$, $\frac{\partial \Pi_{R2}^{vn1}}{\partial s_{r2}} = 0$, $\frac{\partial \Pi_{R2}^{vn1}}{\partial \rho_2} = 0$, $\frac{\partial \Pi_{RC}^{vn1}}{\partial \psi} = 0$, and $\frac{\partial \Pi_{RC}^{vn1}}{\partial p_b} = 0$, we get optimal solution g^{vn1}, $s_{r1}^{nv}, \rho_1^{vn1}$, $s_{r2}^{vn1}, \rho_2^{vn1}, \psi^{vn1}$, and p_b^{vn1}. Using the optimal values, individual profit of each member is obtained.

4.5.5. Vertical Nash (VN2) model 2

In this model structure, all the chain members establish their own decisions independently with the condition that the two retailers play as a single member. In this model structure, manufacturer takes the decision on green level (g) only, and wholesales the products to the retailers at a fixed price.

The decision making power structures are:
Level 1: Manufacturer, max $\Pi_M^{vn2}(g)$ subject to $g > 0$
Level 1: Two retailers (play jointly), max $\Pi_{JR}^{vn2}(s_{ri}, \rho_i)$ subject to $s_{ri} > 0, \rho_i > 0$
Level 1: Recycler, max $\Pi_{RC}^{vn2}(\psi, p_b)$ subject to $0 < (\psi + p_b) < \frac{1}{h}$, $p_b > 0$.

The manufacturer aims to derive optimal profit for the decision on the green level irrespective of others' decisions. Without concerning others, both retailers jointly make decisions on RPs and PEs to optimize their profit. The recycler plans to find out EA_e and buy-back price to achieve maximum profit regardless of others' decisions.

Recalling the propositions 4.4, 4.3, and 4.2, and solving the equations $\frac{\partial \Pi_M^{vn2}}{\partial g} = 0$, $\frac{\partial \Pi_{R1}^{vn2}}{\partial s_{r1}} = 0$, $\frac{\partial \Pi_{R1}^{vn2}}{\partial \rho_1} = 0$, $\frac{\partial \Pi_{R2}^{vn2}}{\partial s_{r2}} = 0$, $\frac{\partial \Pi_{R2}^{vn2}}{\partial \rho_2} = 0$, $\frac{\partial \Pi_{RC}^{vn2}}{\partial \psi} = 0$, and $\frac{\partial \Pi_{RC}^{vn2}}{\partial p_b} = 0$, we get the optimal solution g^{vn2}, s_{r1}^{nvc}, ρ_1^{vn2}, s_{r2}^{vn2}, ρ_2^{vn2}, ψ^{vn2}, and p_b^{vn2}. Using the optimal values, individual profit of the members is achieved.

5. Discussion of results

In this section, with the help of a numerical illustration, we examine the sensitivity of the essential parameters as well as the behavior of the present model.

5.1. Numerical example

We analyze the proposed model numerically under different model structures. Due to the difficulty of accessing accurate industry data, we considered some hypothetical data from previous related research that was compatible with our model assumption. We adopt input parameter values of earlier studies (Bai et al. (2019) and Mondal and Giri (2022)) as far as possible. As our model is somehow dissimilar to the previous literature, some additions and modifications of data are made without violating model assumptions. We use input parameters data of Table 3 to perform the numerical experiments. Tables 4 and 5 present the various optimal outcomes of different systems for the input data.

Table 3. Input data.

		Parameters of the manufacturer		
C_{ms}=\$360/unit	C_{mc}=\$330/unit	C_{co}=\$260/unit	C_e=\$2.5/kg	C=5000 kg
a=50kg/unit	b=0.45	α=0.05	β=0.03	
		Parameters of the retailers		
	k_1=12	k_2=13		
		Parameters of the recycler		
C_s=\$5/unit	h=0.005	x=0.8	l=22	
		Demand parameters		
γ_1=510	γ_2=500	δ=0.45	ζ= 0.85	η= 0.4
	λ=0.75	μ=0.3		

Table 4. Optimal decisions of all model structures.

Model type	Optimal decisions								
	s_{m1} (\$/unit)	s_{m2} (\$/unit)	g	s_{r1} (\$/unit)	s_{r2} (\$/unit)	ρ_1	ρ_2	ψ	p_b (\$/unit)
CS	585.728	591.815	69.167	791.525	789.087	17.814	16.772	11.417	123.791
MS1	820.929	818.963	69.167	951.455	948.016	9.323	8.799	6.044	114.478
MS2	821.036	819.036	69.167	1008.45	1005.25	8.066	7.585	4.577	115.211
RCS	585.728	591.815	51.766	855.045	855.594	14.283	13.105	8.203	114.513
VN1	585.728	591.815	49.618	793.871	793.393	14.867	13.744	9.683	112.658
VN2	585.728	591.815	53.124	885.211	885.785	12.993	11.876	7.355	113.823

Table 5. Optimal outcome of all model structures (CE: Carbon emission, PR: Product recovery rate).

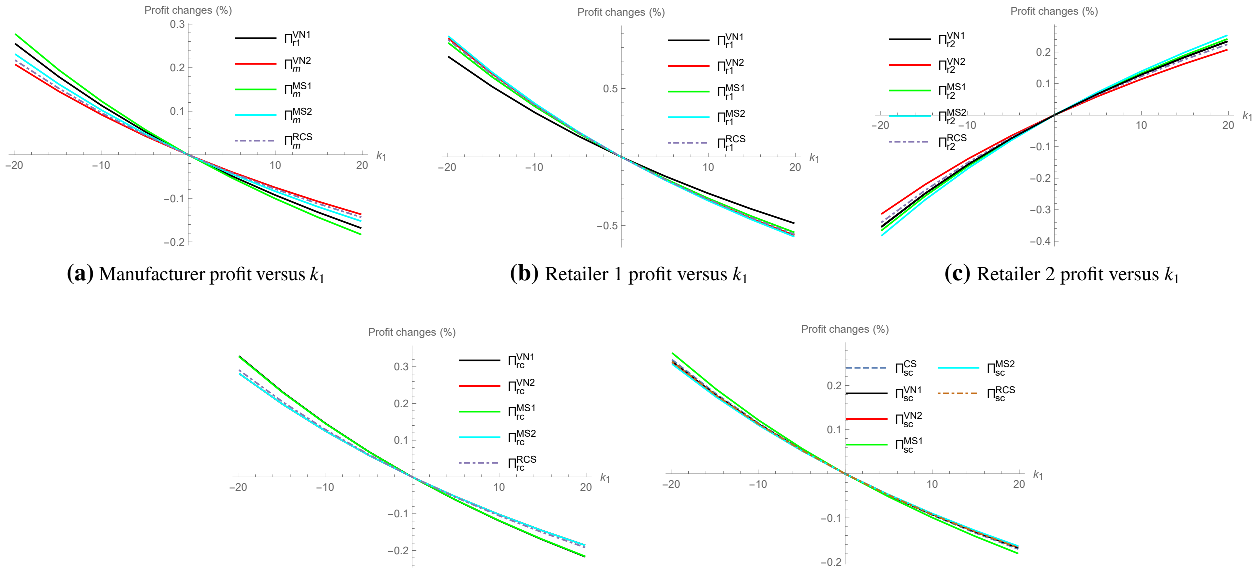
Model type	Market demand		CE	PR	Optimal profit				
	D_1	D_2			Π_M (\$)	Π_{R1} (\$)	Π_{R2} (\$)	Π_{RC} (\$)	Π_{SC} (\$)
CS	187.293	184.245	7381.88	0.676	63058.7	36878.1	34799.3	26499	**161235**
MS1	110.947	109.696	4383.83	0.603	**93149.7**	14025.2	13730.8	15623	136529
MS2	84.817	83.314	3340.49	0.599	73956.2	15554.1	15197.5	11832.3	116540
RCS	150.524	143.602	8268.18	0.614	55781.7	39467.7	36934.5	21004.1	153188
VN1	176.922	171.341	10144.3	0.612	64052	35664.5	33499.4	25031.6	158248
VN2	136.972	130.082	7335.34	0.606	51575.6	**40134.5**	**37464.4**	19012	148187

5.1.1. Numerical observation

The following observations are drawn from Tables 4 and 5. The chain profit meets with the highest value in the CS among all other Stackelberg and Nash models. All the decision variables take the highest value in the CS compared with other systems, and the resultant effect lifts chain profit to the peak. The manufacturer collects maximum individual profit in the MS1 model. It is evident since the manufacturer makes extreme GT investments and charges a higher wholesale price to retailers. Each retailer acquires the highest personal profit in the VN2 model, where they jointly play to optimize their profit. It is entirely rational as the retailers' RPs are reasonably high with moderate PEs compared with other models. The recycler achieves maximum individual profit in the CS, where PR meets the desired level due to the highest value EA_e and buy-back price. Among DS, maximum PR occurs in the RCS model as the retailers and recyclers jointly play the role of leader. The green level of the product takes the highest value in the manufacturer's Stackelberg model, among other decentralized structures, as the manufacturer performs as a leader. The green investment works significantly in the proposed model; whenever g increases, the emission amount decreases correspondingly. The used PR is also effective in the model; increasing EA_e and the buy-back price increases the recovery rate. From a profit perspective, a thorough inspection reveals that the CS is the most acceptable and desirable model for all DS for the chain.

5.2. *Discussion on parameters' sensitivity*

We examine the sensitivity of the decision variables along with individual member profit, chain profit, CE, and PR rate for all scenarios with the changes of the critical parameters $k_1, k_2, \delta, \beta, \eta, \mu$, and λ by fixing the remaining parameters' value as mentioned in the Subsection 5.1. The sensitivity analysis with respect to the parameters shows the stability and reliability of the work. The analysis shows that the model is not only appropriate for fixed data, but it is also applicable within a range of the given data. Table 6 (see Appendix E) presents the variation of decision variables, CE, and PR rate. Moreover, percentage changes of the individual profit and chain profit corresponding to the changes of the parameters for all game approaches are depicted in Figures 3 to 6.



(a) Manufacturer profit versus k_1 **(b)** Retailer 1 profit versus k_1 **(c)** Retailer 2 profit versus k_1

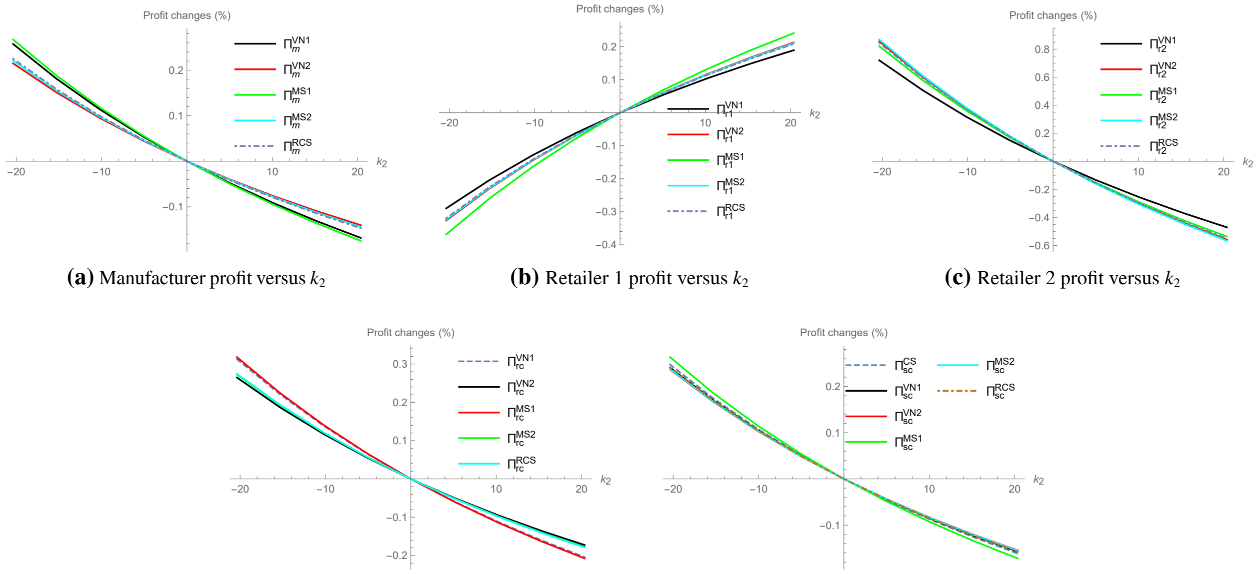
(d) Recycler profit versus k_1 **(e)** Chain profit versus k_1

Figure 3. Variation of profit functions with the changes of k_1.

5.2.1. Effects of promotional effort cost coefficients k_1 and k_2

From Table 6, the impact of k_1 and k_2 are quite significant on effort level ρ_1, and ρ_2 respectively, for all scenarios, whereas trivial changes are noticed in all other decision variables. Both parameters have a marginal effect on CE in all model structures. Since increasing k_1 results in higher promotional costs, the first retailer makes a substantial decrease in ρ_1, corresponding to lower customer demand. Consequently, individual and chain profits take downward movement in all game approaches except the second retailer's profit, which increases interestingly due to the competing behavior among the retailers (see Figure 3). Figure 3b reveals that the first retailer's profit percentage change is lower in the VN1 model, as chain members make independent decisions. Again, higher values of k_2 make promotional costs more significant for the second retailer, which is why they have to reduce effort level to balance expenditure. Therefore, individual member and chain profits decrease except the first retailer's profit, which catches upward movement (depicted in Figure 4).

The above result indicates that each retailer's promotion effort positively influences individual profit. If one retailer's PE cost coefficient increases, then the PE level automatically decreases; for that, the retailer has to decrease the retail price to achieve higher profit. Due to the retailers' rivalry, one retailer's increasing PE cost coefficient provides an opportunity for the other retailer to achieve higher profit.



(a) Manufacturer profit versus k_2 **(b)** Retailer 1 profit versus k_2 **(c)** Retailer 2 profit versus k_2

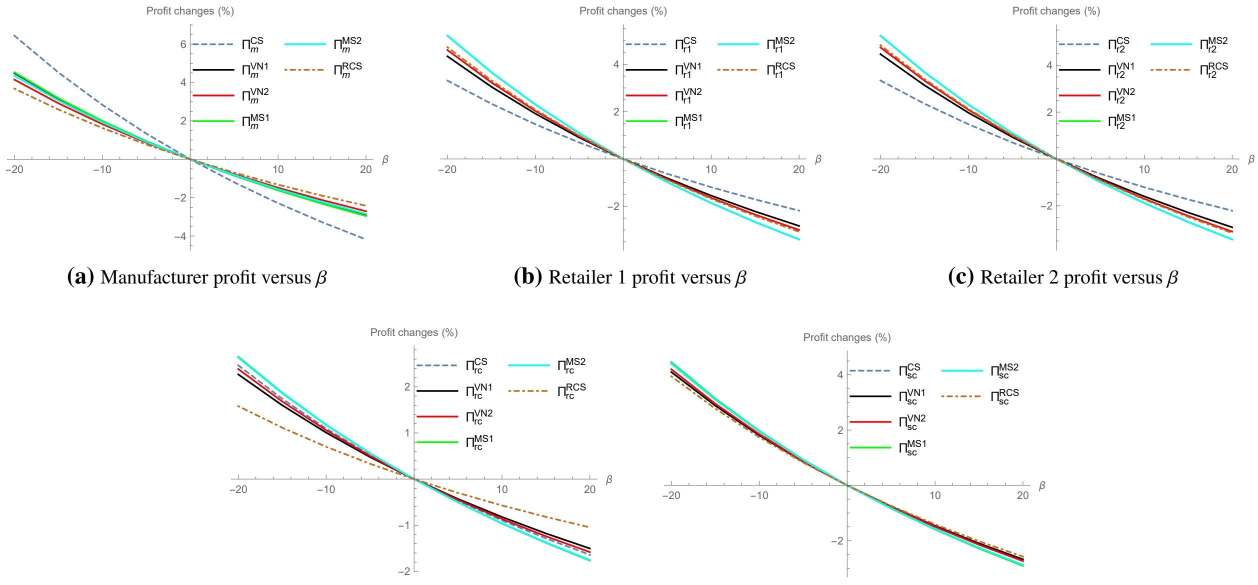
(d) Recycler profit versus k_2 **(e)** Chain profit versus k_2

Figure 4. Variation of profit functions with the changes of k_2.

5.2.2. Effect of parameters β and l

The green level and CE are susceptible to the parameter β compared with others for every system, presented in Table 6. We notice that CE boosts up exceptionally due to a splendid reduction of g with higher β. For the higher green cost, the manufacturer has to reduce the product's green level, which decreases customer demand. As a consequence, the individual profit of players and chain profit move downwards in every game structure with increasing β (Figure 5). Again, Table 6 illustrates that l significantly impacts EA_e and moderately impacts buy-back price in all game models. Increasing l leads EA_e level downwards, which leads to a lower PR rate. In Figure 6, recycler profit and chain profit fall in all game approaches due to the reduction of PR. Each retailer's profit is inversely proportional to l for all scenarios except RCS, where corresponding profits are lifted due to retailers' dominating powers.

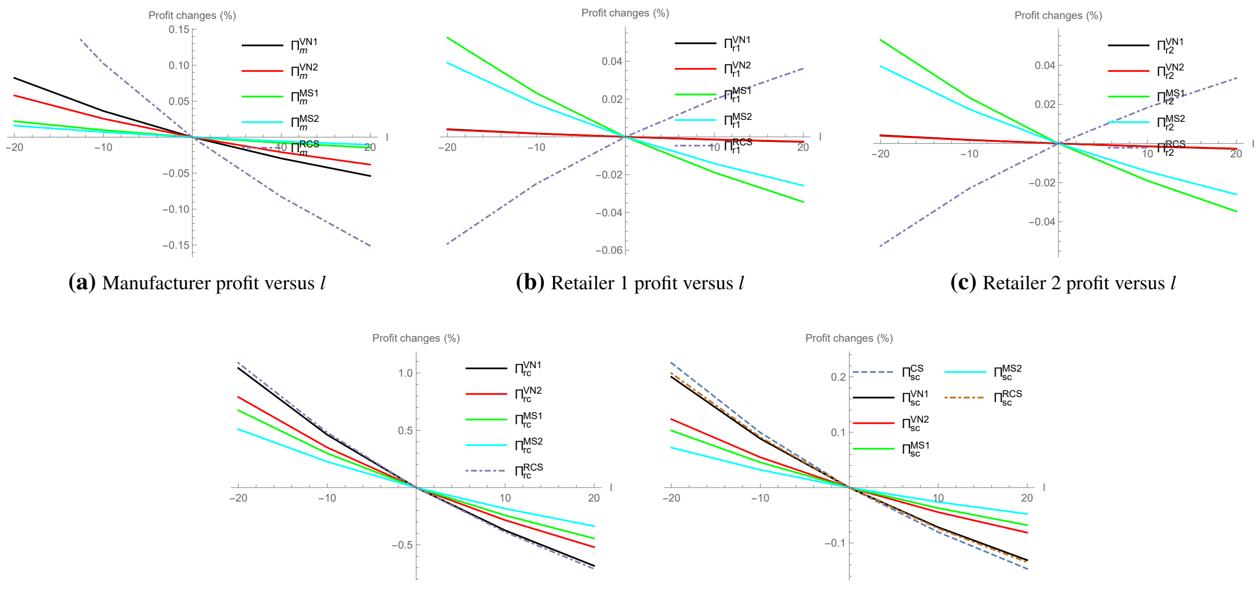
The above result shows that the higher green investment cost coefficient lowers the green level, and for that, all the members have to decrease their corresponding selling prices to avoid a non-profitable situation. Again, when the investment cost coefficient is lower, the manufacturer can reduce the emissions amount by spending more on green investments. A lower EA cost coefficient increases PR, and all members achieve higher profits.



(a) Manufacturer profit versus β **(b)** Retailer 1 profit versus β **(c)** Retailer 2 profit versus β

(d) Recycler profit versus β **(e)** Chain profit versus β

Figure 5. Variation of profit functions with the changes of β.



(a) Manufacturer profit versus l **(b)** Retailer 1 profit versus l **(c)** Retailer 2 profit versus l

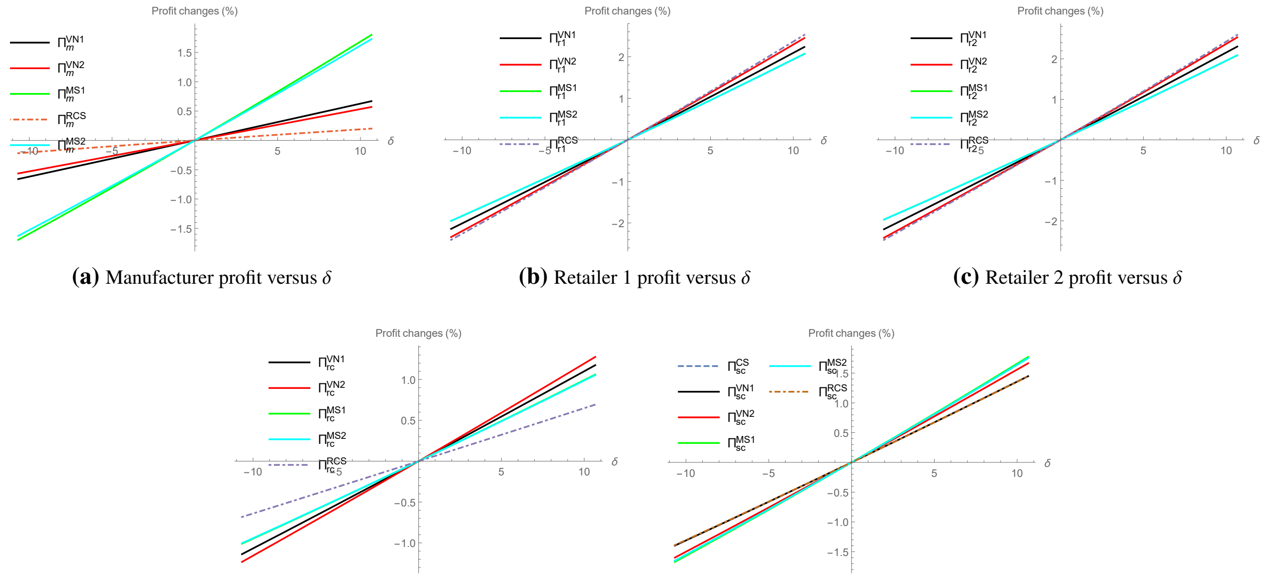
(d) Recycler profit versus l **(e)** Chain profit versus l

Figure 6. Variation of profit functions with the changes of l.

5.2.3. Effect of δ

Table 6 reflects that increasing δ generates a higher green level, leading to greater customer demand. From Figure 7, we observe that each member's and chain profits hike up in all model structures due to the collective positive impact of demand increment.

Here, the higher values of δ make CE lower, and the reduction in CE cost compels all the chain members into a better profitable situation.



(a) Manufacturer profit versus δ **(b)** Retailer 1 profit versus δ **(c)** Retailer 2 profit versus δ

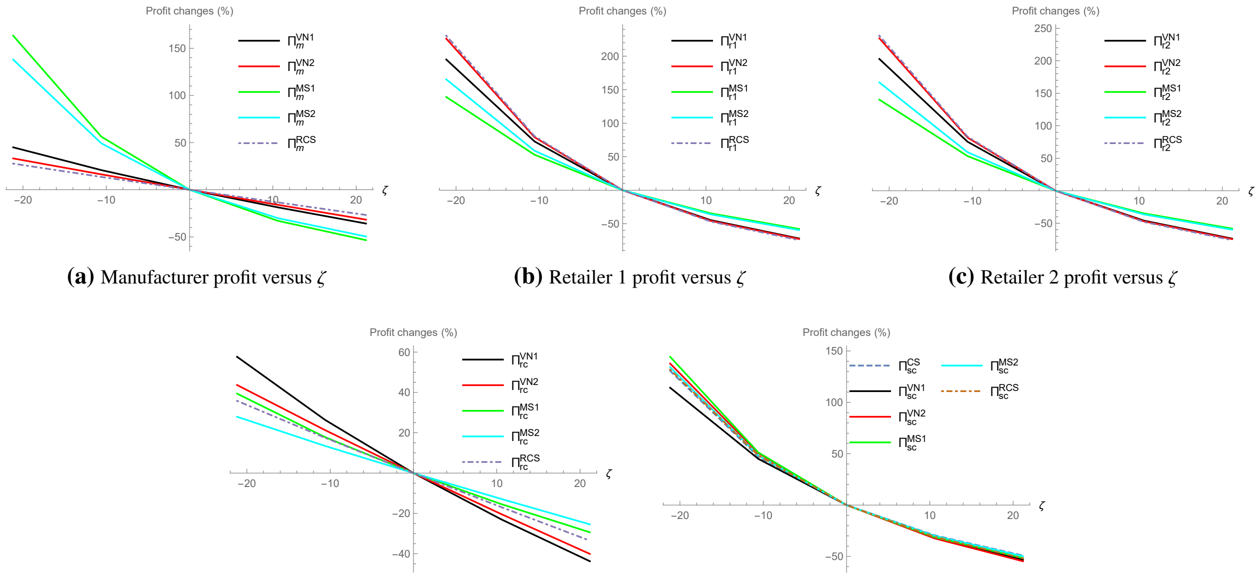
(d) Recycler profit versus δ **(e)** Chain profit versus δ

Figure 7. Variation of profit functions with the changes of δ.

5.2.4. Effect of price-sensitive parameters ζ and η

The ζ is the most hypersensitive parameter among all. Table 6 and Figure 8 reveal that all the decision variables, CE, along with individual and chain profit, are severely affected by ζ for all model structures. With higher ζ, RP and PE catch downward movement, resulting in unprecedented customer demand, which leads to acute decrement in both retailers' profit. Surprisingly, the green level increases in CS, MS1, and MS2 but decreases in RCS, VN1, and VN2 models, reflecting its impact on CE. Rigorous changes in manufacturer profit in CS, MS1, and MS2, retailers' profit in RCS, VN2, and VN2, and recycler's profit in VN1 and VN2 are noticed with switching ζ because each player achieves a higher profit in the mentioned scenarios than in other scenarios. Again, η is the second hypersensitive parameter. In Table 6, remarkable RP, PE, and EA_e increments are observed with uprising η for CS and all DS. Increasing RP and PE corresponds to higher demand for that individual and chain profits rise in all game approaches (see Figure 9).

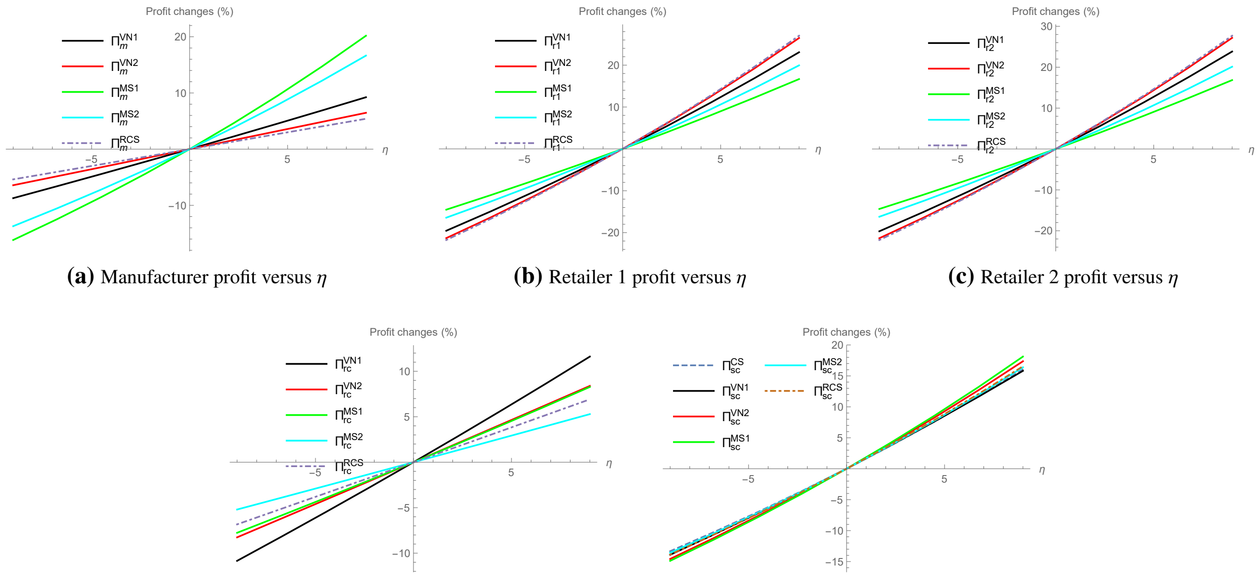
The above result shows that both retailers must decrease their corresponding retail prices to maintain a profitable situation with the increasing price-sensitive parameter.



(a) Manufacturer profit versus ζ **(b)** Retailer 1 profit versus ζ **(c)** Retailer 2 profit versus ζ

(d) Recycler profit versus ζ **(e)** Chain profit versus ζ

Figure 8. Variation of profit functions with the changes of ζ.



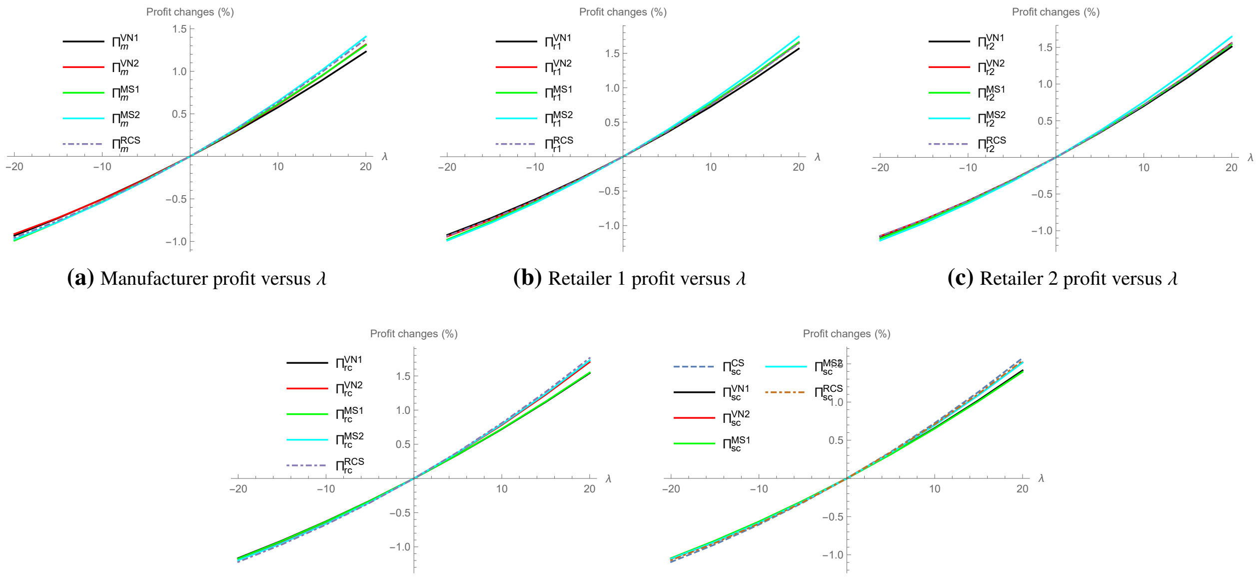
(a) Manufacturer profit versus η **(b)** Retailer 1 profit versus η **(c)** Retailer 2 profit versus η

(d) Recycler profit versus η **(e)** Chain profit versus η

Figure 9. Variation of profit functions with the changes of η.

5.2.5. Effect of PE-sensitive parameters λ and μ

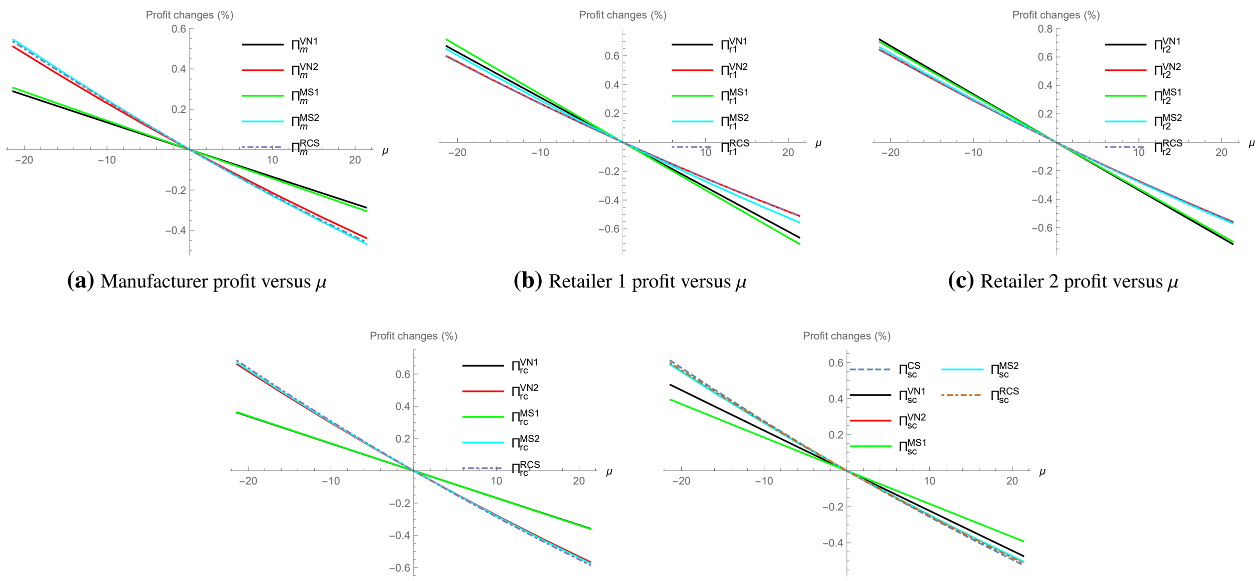
The λ causes sharp changes in PE levels for all game models, whereas the remaining decision variables are minor sensitive. Table 6 reveals that, with ascending λ, the effort level of both retailers ρ_1 and ρ_2 take upward values, which corresponds to higher demand. Due to the impact of demand hiking, the members' profit and chain profit lift for all scenarios (depicted in Figure 10). Again, we observe from Table 6 that μ creates minor changes to all the decision variables. As μ increases, effort levels of both retailers decrease, which impacts negatively the customer demand and that individual and chain profits fall in all game structures (illustrated in Figure 11).



(a) Manufacturer profit versus λ **(b)** Retailer 1 profit versus λ **(c)** Retailer 2 profit versus λ

(d) Recycler profit versus λ **(e)** Chain profit versus λ

Figure 10. Variation of profit functions with the changes of λ.



(a) Manufacturer profit versus μ **(b)** Retailer 1 profit versus μ **(c)** Retailer 2 profit versus μ

(d) Recycler profit versus μ **(e)** Chain profit versus μ

Figure 11. Variation of profit functions with the changes of μ.

The above result reveals that increasing promotional influence parameter makes higher PE and, for that reason, both retailers' acquire lofty profit.

5.2.6. Effect of carbon cap parameter C

Figure 12 illustrates that the manufacturer's profit is influenced by the carbon emission quota. With the rising carbon emission limit, profit of the manufacturer increases in all the model structures. Here, the manufacturer has to pay for lower additional emissions units than before if the offered carbon quota is higher. As a result, the CE costs of the manufacturer have been reduced and the manufacturer achieves greater profit.

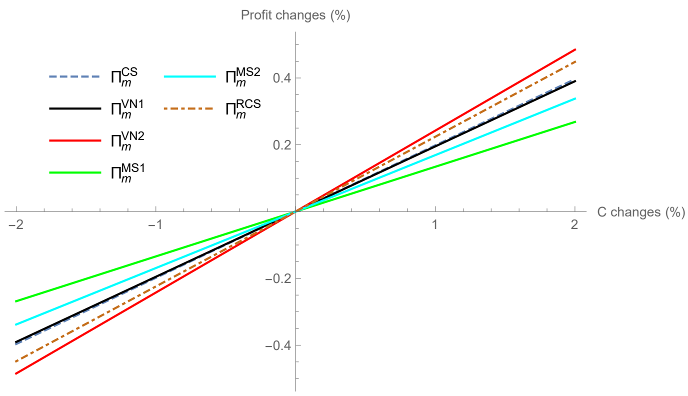


Figure 12. Manufacturer profit versus C.

5.2.7. Effect of the parameter α

Figure 13 illustrates that the manufacturer's profit is severely influenced by α. With the increasing α, profit of the manufacturer decreases in all the model structures. Table 6 reveals that α causes sharp changes in CE amount for all game models, whereas the changes of remaining decision variables can be neglected. Due to the increasing production rate of imperfect items, the manufacturer has to increase overall production quantity to satisfy both retailers' demand. Consequently, more production generates higher CE. As a result, the production costs and carbon emissions costs of the manufacturer increase, which causes lower profit for the manufacturer.

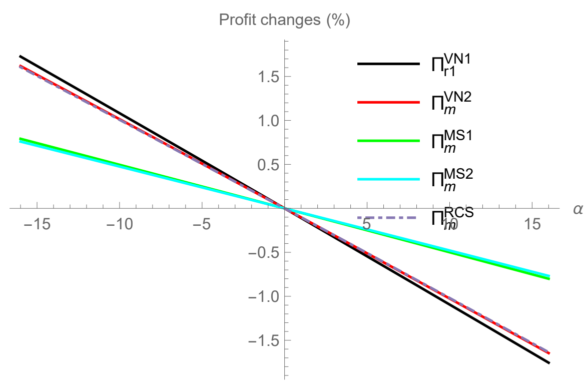


Figure 13. Manufacturer profit versus α.

5.3. Managerial implications

In the proposed study, some significant findings with managerial implications are derived, which can be utilized by the chain members.

- The model explores that GT investment is effective in reducing CE. When the green investment cost coefficient is higher (the green level is lower), the manufacturer and the retailers must decrease their selling prices to maintain the market demand; otherwise, they face profit loss. Therefore, business organizations could abate and restrict emissions using green investment and gain higher economic and environmental growth.
- The sensitivity results highlight that PE positively impacts product selling. If the PE cost coefficient of one retailer is more significant (PE level is lower), then the retailer has to decrease their retail price to achieve more substantial profit, whereas another retailer may hike up their retail price due to the competitive behavior between them. Therefore, chain members who know the PE strategy could increase market demand and their profits to a satisfactory level.
- The selling price plays an essential role in enhancing market sales. When the price sensitivity parameter (ζ) increases, both players have to lower their corresponding selling prices and may increase GT investment to adjust demand and reputation in the market. Therefore, chain members with the proper pricing strategy could enhance chain operations and attain profit goals.
- To reduce production costs, curtail emissions, manage waste, balance natural resources, and move towards sustainable development, chain members prefer PR. The model presents that the EN_e and buy-back price-sensitive PR rate effectively recover used products. When the EN_e cost coefficient increases, the recycler has to offer a lower buy-back price to adjust the PR rate. Therefore, a chain member who is aware of product recycling strategies could promote chain performance by fulfilling environmental goals for more significant economic benefit.

6. Concluding remarks

In the present situation, due to shortages of natural resources and rapid increment in environmentally conscious customers, product recycling and low-carbon products are getting intense attention not only from the manager of the supply chain but also from researchers in supply chain management. This article explores a green environment SCnM with imperfect production and recycling of used products under the governmental initiative CT policy. The recycler invests in EA and offers the best buy-back price to the end customers to enhance PR. This study considers the rivalry between the retailers in the RP and PE-based market. A CS and five different DS are presented to analyze the proposed model. In environmental and economic aspects, the following results are examined:

1. Green level and recovery rate attain the highest value in the CS, and their effectiveness is satisfactory in the present study.
2. In a competitive market, one retailer's demand is more severely sensitive to RP than PE.
3. The CS yields a more significant overall profit by enhancing chain performance compared with DS.
4. Among the DS, integrated chain profit is highest in the Vertical Nash 1 model, close to the CS.

From the above insights, the model's implications are as follows: The model demonstrates that GT investments effectively reduce CE. In this way, business organizations could reduce their emissions and achieve higher economic and environmental growth using green investment. PE has a positive impact on product sales. As a result, chain members who know the PE strategy could increase their profits to a satisfactory level. A chain member can increase profits and enhance chain operations with the appropriate pricing strategy. Chain members prefer PR to reduce production costs and manage waste. Therefore, a chain member who is aware of product recycling strategies can contribute to chain performance by meeting environmental goals while gaining significant economic benefits. By exercising this model, the chain managers with detailed operational information on proper pricing strategy, green investment, knowledge of the PE, EA_e, and proper buy-back price technique could enhance the chain performance from both environmental and economic perspectives.

According to the present study, considering a single green manufacturer without a separate remanufacturing unit under deterministic demand is the main limitation of our research. The proposed model should have considered product and product quality shortages due to uncertainty phenomena in the supply and production system. The proposed model may be extended immediately, incorporating the above issues. For future research, one can extend the model under trade credit policy with partial payment and inflation. Another extension may be possible by including multiple manufacturers, retailers, etc. One is to introduce manufacturers and retailers instead of recyclers for used PR in future studies. To ensure a win-win situation, an agreement between the players to coordinate the chain members will be worth investigating in a future study. The present model can be explored by analyzing other emission reduction incentives implemented by the government in further research.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

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A. Proof of the Proposition 4.1

Proof. Solving $\frac{\partial \Pi_{R1}^{ms1}}{\partial s_{r1}} = 0$, $\frac{\partial \Pi_{R1}^{ms1}}{\partial \rho_1} = 0$, $\frac{\partial \Pi_{R2}^{ms1}}{\partial s_{r2}} = 0$, and $\frac{\partial \Pi_{R2}^{ms1}}{\partial \rho_2} = 0$, we obtain the solution

$$s_{r1}^{ms1} = \frac{g(2\delta\zeta k_1 k_2 + \delta\eta k_1 k_2 - \delta\lambda^2 k_1 - \delta\lambda k_1\mu) + E_2}{E_1},$$
$$\rho_1^{ms1} = \frac{g(2\delta\zeta\lambda k_2 + \delta\eta\lambda k_2 - \delta\lambda^3 - \delta\lambda^2\mu) + E_4}{E_1},$$
$$s_{r2}^{ms1} = \frac{g(2\delta\zeta k_1 k_2 + \delta\eta k_1 k_2 - \delta\lambda^2 k_2 - \delta\lambda k_2\mu) + E_3}{E_1},$$
$$\rho_2^{ms1} = \frac{g(2\delta\zeta\lambda k_1 + \delta\eta\lambda k_1 - \delta\lambda^3 - \delta\lambda^2\mu) + E_5}{E_1}$$

where, $E_1 = k_1k_2(4\zeta^2 - \eta^2) + (k_1 + k_2)(\eta\lambda\mu - 2\zeta\lambda^2) + \lambda^2(\lambda^2 - \mu^2)$,
$E_2 = k_1k_2(\gamma_2\eta + 2\gamma_1\zeta + \zeta\eta s_{m2} + 2\zeta^2 s_{m1}) + k_2(\eta\lambda\mu s_{m1} - 2\zeta\lambda^2 s_{m1}) + k_1(\zeta\lambda\mu s_{m2} - \gamma_2\lambda\mu - \gamma_1\lambda^2 - \eta\lambda^2 s_{m2} - \zeta\lambda^2 s_{m1}) + \lambda^2 s_{m1}(\lambda^2 - \mu^2)$,
$E_3 = k_1k_2(\gamma_1\eta + 2\gamma_2\zeta + \zeta\eta s_{m1} + 2\zeta^2 s_{m2}) + k_1(\eta\lambda\mu s_{m2} - 2\zeta\lambda^2 s_{m2}) + k_2(\zeta\lambda\mu s_{m1} - \gamma_1\lambda\mu - \gamma_2\lambda^2 - \eta\lambda^2 s_{m1} - \zeta\lambda^2 s_{m2}) + \lambda^2 s_{m2}(\lambda^2 - \mu^2)$,
$E_4 = k_2(\gamma_2\eta\lambda + 2\gamma_1\zeta\lambda + \zeta\eta\lambda s_{m2} - 2\zeta^2\lambda s_{m1} + \eta^2\lambda s_{m1}) + (\zeta\lambda^2\mu s_{m2} - \gamma_2\lambda^2\mu - \gamma_2\lambda^3 - \eta\lambda^3 s_{m2} + \zeta\lambda^3 s_{m1} - \eta\lambda^2\mu s_{m1})$,
$E_5 = k_1(\gamma_1\eta\lambda + 2\gamma_2\zeta\lambda + \zeta\eta\lambda s_{m1} - 2\zeta^2\lambda s_{m2} + \eta^2\lambda s_{m2}) + (\zeta\lambda^2\mu s_{m1} - \gamma_1\lambda^2\mu - \gamma_2\lambda^3 - \eta\lambda^3 s_{m1} + \zeta\lambda^3 s_{m2} - \eta\lambda^2\mu s_{m2})$
The HN_m of the profit function Π_{Ri}^{ms1} at $(s_{ri}^{ms1}, \rho_i^{ms1})$ is

$$H_{Ri} = \begin{pmatrix} -2\zeta & \lambda \\ \lambda & -k_i \end{pmatrix}$$

Therefore, H_{Ri} is negative definite if $2\zeta k_i - \lambda^2 > 0$.
Hence, the profit function $\Pi_{Ri}^{ms1}(s_{ri}, \rho_i)$ is maximum at $(s_{ri}^{ms1}, \rho_i^{ms1})$ if the condition $2\zeta k_i - \lambda^2 > 0$ holds.

B. Proof of the Proposition 4.2

Proof. Solving the equations $\frac{\partial \Pi_{RC}^{ms1}}{\partial \psi} = 0$, $\frac{\partial \Pi_{RC}^{ms1}}{\partial p_b} = 0$, we get the solution
$\psi^{ms1} = \frac{h(C_s - xC_{mc})(D_1' + D_2')}{h(D_1' + D_2') - 2l}$, $p_b^{ms1} = \frac{(C_s - xC_{mc})(hD_1' + hD_2' - l)}{h(D_1' + D_2') - 2l}$.
This solution is optimal if the HN_m of the profit function is negative definite at (ψ^{ms1}, p_b^{ms1}).
The HN_m of the profit function Π_{RC}^{ms1} at (ψ^{ms1}, p_b^{ms1}) is

$$H_{RC}^{ms1} = \begin{pmatrix} -l & h(D_1' + D_2') \\ h(D_1' + D_2') & -2h(D_1' + D_2') \end{pmatrix}$$

H_{RC}^{ms1} is negative definite if $2hl(D_1' + D_2') - h^2(D_1' + D_2')^2 > 0$, i.e., if $2l > h(D_1' + D_2')$

Hence, the HN_m is negative definite if the condition $2l > h(D_1' + D_2')$ is satisfied.
Therefore, Π_{RC}^{ms1} is maximum at
$\psi^{ms1} = \frac{h(C_s - xC_{mc})(D_1' + D_2')}{h(D_1' + D_2') - 2l}$, $p_b^{ms1} = \frac{(C_s - xC_{mc})(hD_1' + hD_2' - l)}{h(D_1' + D_2') - 2l}$, if the condition $2l > h(D_1' + D_2')$ holds.

C. Proof of the Proposition 4.3

Proof. The HN_m of the profit function $\Pi_{JR}^{ms2}(s_{ri}, \rho_i)$ is

$$H_{JR}^{ms2} = \begin{pmatrix} \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial s_{r1}^2} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial s_{r1} \partial s_{r2}} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial s_{r1} \partial \rho_1} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial s_{r1} \partial \rho_2} \\ \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial s_{r2} \partial s_{r1}} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial s_{r2}^2} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial s_{r2} \partial \rho_1} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial s_{r2} \partial \rho_2} \\ \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial \rho_1 \partial s_{r1}} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial \rho_1 \partial s_{r2}} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial \rho_1^2} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial \rho_1 \partial \rho_2} \\ \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial \rho_2 \partial s_{r1}} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial \rho_2 \partial s_{r2}} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial \rho_2 \partial \rho_1} & \frac{\partial^2 \Pi_{JR}^{ms2}}{\partial \rho_2^2} \end{pmatrix} = \begin{pmatrix} -2\zeta & 2\eta & \lambda & -\mu \\ 2\eta & -2\zeta & -\mu & \lambda \\ \lambda & -\mu & -k_1 & 0 \\ -\mu & \lambda & 0 & -k_2 \end{pmatrix}$$

The matrix H_{JR}^{ms2}, is negative definite if the p^{th} order leading principal minor, Δ_p take the sign $(-1)^p$ for $p = 1, 2, 3, 4$, i.e., $\Delta_1 < 0$, $\Delta_2 > 0$, $\Delta_3 < 0$, $\Delta_4 > 0$.
Here,

$$\Delta_1 = -2\zeta < 0$$

$$\Delta_2 = \begin{vmatrix} -2\zeta & 2\eta \\ 2\eta & -2\zeta \end{vmatrix} > 0 \text{ if } 4(\zeta^2 - \eta^2) > 0,$$

$$\text{i.e., if } \zeta > \eta \tag{13}$$

$$\Delta_3 = \begin{vmatrix} -2\zeta & 2\eta & \lambda \\ 2\eta & -2\zeta & -\mu \\ \lambda & -\mu & -k_1 \end{vmatrix} < 0 \text{ if } 2\zeta\left(\lambda^2 + \mu^2\right) - 4\eta\lambda\mu - 4k_1\left(\zeta^2 - \eta^2\right) < 0,$$

$$\text{i.e., if } 2\zeta\left(\lambda^2 + \mu^2\right) < 4\eta\lambda\mu + 4k_1\left(\zeta^2 - \eta^2\right) \tag{14}$$

$$\Delta_4 = \left|H_{JR}^{ms2}\right| > 0$$

$$\text{if } \left(\lambda^2 - \mu^2\right)^2 + k_1\left(-2\zeta\left(\lambda^2 + \mu^2\right) + 4\eta\lambda\mu + 4k_2\left(\zeta^2 - \eta^2\right)\right) - 2\zeta k_2\left(\lambda^2 + \mu^2\right) + 4\eta\lambda k_2\mu > 0$$

$$\text{i.e., if } \left(\lambda^2 - \mu^2\right)^2 + k_1\left(4\eta\lambda\mu + 4k_2\left(\zeta^2 - \eta^2\right)\right) + 4\eta\lambda k_2\mu > 2\zeta(k_1 + k_2)\left(\lambda^2 + \mu^2\right) \tag{15}$$

Hence, the profit function Π_{JR}^{ms2} is concave on s_{r1}, s_{r2}, ρ_1, and ρ_2 if the conditions of (13), (14), and (15) hold.

D. Proof of the Proposition 4.4

Proof. Substituting the values of D_1 and D_2 in equation (11), we obtain the first and second order derivative of $\Pi_M^{rcs}(g)$ with respect to g

$$\frac{\partial \Pi_M^{rcs}}{\partial g} = (s_{m1} + s_{m2})\delta + 2\delta hx(p_b + \psi)(C_{ms} - C_{mc}) - 2C_{ms}\delta - \frac{1}{1-\alpha}\Big(2C_{co}\alpha\delta + g^2\beta\delta + 2C_e(a - bg)\delta$$

$$+ (g\beta - bC_e)(\gamma_1 + \gamma_2 + 2g\delta - s_{r1}\zeta - s_{r2}\zeta + s_{r1}\eta + s_{r2}\eta + \lambda\rho_1 - \mu\rho_1 + \lambda\rho_2 - \mu\rho_2)\Big)$$

$$\frac{\partial^2 \Pi_M^{rcs}}{\partial g^2} = \frac{1}{\alpha - 1}\Big(\beta(\gamma_1 + \gamma_2 + 6g\delta - s_{r1}\zeta - s_{r2}\zeta + s_{r1}\eta + s_{r2}\eta + \lambda\rho_1 - \mu\rho_1 + \lambda\rho_2 - \mu\rho_2) - 4bC_e\delta\Big) \quad (16)$$

Now, $\Pi_M^{rcs}(g)$ will be concave if the second order condition $\frac{\partial^2 \Pi_M^{rcs}}{\partial g^2} < 0$ is satisfied.
From the equation (16),

$$\frac{\partial^2 \Pi_M^{rcs}}{\partial g^2} < 0 \text{ if } \frac{1}{\alpha - 1}\Big(\beta(\gamma_1 + \gamma_2 + 6g\delta - s_{r1}\zeta - s_{r2}\zeta + s_{r1}\eta + s_{r2}\eta + \lambda\rho_1 - \mu\rho_1 + \lambda\rho_2 - \mu\rho_2) - 4bC_e\delta\Big) < 0$$

$$\text{i.e. if } g < \frac{1}{6\beta\delta}\Big(4bC_e\delta + \beta(-\gamma_1 - \gamma_2 + s_{r1}\zeta + s_{r2}\zeta - s_{r1}\eta - s_{r2}\eta - \lambda\rho_1 + \mu\rho_1 - \lambda\rho_2 + \mu\rho_2)\Big)$$

Hence, $\Pi_M^{rcs}(g)$ is concave in g if the condition $g < \frac{1}{6\beta\delta}\Big(4bC_e\delta + \beta(-\gamma_1 - \gamma_2 + s_{r1}\zeta + s_{r2}\zeta - s_{r1}\eta - s_{r2}\eta - \lambda\rho_1 + \mu\rho_1 - \lambda\rho_2 + \mu\rho_2)\Big)$ holds.

E. Sensitivity table

Table 6. Changes in the optimal values with the variation of key parameters

Parameter with values		Changes in optimal values																	
		VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS
		g						s_{r1}						s_{r2}					
k_1	12.58	49.581	53.084	51.728	69.167	69.167	69.167	795.47	886.73	856.69	952.43	1009.4	793.62	793.08	885.88	855.68	947.86	1005.32	789.24
	11.54	49.601	53.106	51.749	69.167	69.167	69.167	794.58	885.88	855.77	951.89	1008.87	792.45	793.25	885.83	855.63	947.95	1005.28	789.15
	10.5	49.618	53.124	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
	9.46	49.631	53.138	51.779	69.167	69.167	69.167	793.29	884.66	854.45	951.1	1008.1	790.77	793.51	885.75	855.56	948.07	1005.22	789.03
	8.42	49.642	53.15	51.791	69.167	69.167	69.167	792.81	884.21	853.96	950.81	1007.82	790.14	793.6	885.72	855.54	948.12	1005.2	788.99
		ρ_1						ρ_2						ψ					
		18.683	16.334	17.957	11.722	10.141	22.397	13.722	11.841	13.068	8.7823	7.5639	16.726	9.7151	7.3754	8.2267	6.0634	4.5901	11.45
		16.558	14.473	15.911	10.386	8.9856	19.845	13.734	11.86	13.089	8.7917	7.5756	16.751	9.6975	7.3639	8.2136	6.0524	4.583	11.432
		14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
		13.49	11.787	12.957	8.458	7.3177	16.161	13.752	11.888	13.118	8.8052	7.5925	16.788	9.672	7.3473	8.1947	6.0366	4.5727	11.405
		12.346	10.786	11.857	7.7396	6.6962	14.788	13.758	11.899	13.129	8.8102	7.5988	16.802	9.6625	7.3411	8.1876	6.0307	4.5688	11.395
		p_b						Carbon emissions						Product recovery rate					
		112.64	113.81	114.5	114.47	115.2	123.77	10182.	7360.4	8296.6	4397.8	3349.7	7402.4	0.6118	0.6059	0.6136	0.6027	0.599	0.6761
		112.65	113.82	114.51	114.47	115.21	123.78	10161.	7346.4	8280.8	4390.	3344.6	7391.	0.6117	0.6059	0.6136	0.6026	0.599	0.6761
		112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
		112.66	113.83	114.52	114.48	115.21	123.8	10131.	7326.3	8257.9	4378.8	3337.2	7374.5	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
		112.67	113.83	114.52	114.48	115.22	123.8	10119.	7318.8	8249.4	4374.6	3334.4	7368.4	0.6117	0.6059	0.6135	0.6026	0.5989	0.676
		g						s_{r1}						s_{r2}					
k_2	12.12	49.583	53.086	51.73	69.167	69.167	69.167	793.57	885.3	855.13	951.3	1008.52	791.67	794.92	887.22	857.15	948.97	1006.17	791.13
	11.56	49.602	53.107	51.75	69.167	69.167	69.167	793.74	885.25	855.08	951.39	1008.48	791.59	794.07	886.42	856.28	948.44	1005.66	789.99
	11.0	49.618	53.124	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
	10.44	49.63	53.137	51.779	69.167	69.167	69.167	793.98	885.18	855.02	951.51	1008.42	791.47	792.84	885.27	855.04	947.68	1004.92	788.36
	9.88	49.641	53.149	51.789	69.167	69.167	69.167	794.07	885.15	854.99	951.55	1008.4	791.43	792.39	884.85	854.57	947.39	1004.64	787.76
		ρ_1						ρ_2						ψ					
		14.846	12.958	14.246	9.3061	8.0449	17.767	17.389	15.032	16.589	11.139	9.6014	21.231	9.7137	7.3742	8.2255	6.0629	4.5898	11.449
		14.858	12.977	14.267	9.3157	8.0569	17.793	15.353	13.269	14.643	9.8316	8.4749	18.74	9.6968	7.3633	8.213	6.0522	4.5828	11.431
		14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
		14.875	13.005	14.296	9.3295	8.074	17.831	12.44	10.747	11.86	7.9629	6.8641	15.178	9.6726	7.3478	8.1952	6.0368	4.5728	11.406
		14.881	13.015	14.307	9.3345	8.0803	17.845	11.362	9.8149	10.83	7.2717	6.2684	13.861	9.6636	7.342	8.1886	6.0311	4.5692	11.396
		p_b						Carbon emissions						Product recovery rate					
		112.64	113.81	114.5	114.47	115.21	123.78	10181.	7359.	8295.1	4397.4	3349.4	7401.8	0.6118	0.6059	0.6136	0.6027	0.599	0.6761
		112.65	113.82	114.51	114.47	115.21	123.78	10160.	7345.8	8280.1	4389.8	3344.4	7390.7	0.6117	0.6059	0.6136	0.6026	0.599	0.6761
		112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
		112.66	113.83	114.52	114.48	115.21	123.8	10131.	7326.9	8258.5	4379.	3337.3	7374.8	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
		112.67	113.83	114.52	114.48	115.22	123.8	10121.	7319.9	8250.6	4374.9	3334.7	7368.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676

Parameter with values	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS
	Changes in optimal values																	
	g						s_{r1}						s_{r2}					
β 0.036 0.033 0.03 0.027 0.024	62.192	66.5534	64.993	86.458	86.458	86.458	798.34	892.07	863.48	962.65	1021.12	799.49	797.85	892.64	864.02	959.21	1017.91	797.04
	55.199	59.0865	57.632	76.852	76.852	76.852	795.85	888.26	858.79	956.43	1014.08	795.06	795.37	888.83	859.33	952.99	1010.88	792.62
	49.618	53.1238	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
	45.06	48.2529	46.981	62.879	62.879	62.879	792.25	882.72	851.99	947.38	1003.84	788.63	791.78	883.3	852.54	943.95	1000.64	786.19
	41.268	44.1992	43.004	57.639	57.639	57.639	790.91	880.65	849.46	943.99	1000.	786.22	790.43	881.23	850.01	940.56	996.802	783.78
	ρ_1						ρ_2						ψ					
	15.186	13.287	14.498	9.563	8.2734	18.232	14.048	12.156	13.31	9.0275	7.7821	17.17	9.9031	7.5302	8.3503	6.204	4.6979	11.699
	15.009	13.123	14.378	9.4298	8.1583	18.	13.879	12.	13.196	8.9006	7.6726	16.949	9.7809	7.4326	8.2685	6.1149	4.6309	11.542
	14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
	14.752	12.886	14.205	9.2361	7.991	17.662	13.634	11.774	13.031	8.7161	7.5132	16.627	9.6039	7.2912	8.1498	5.9855	4.5335	11.315
	14.656	12.797	14.141	9.1635	7.9283	17.536	13.542	11.689	12.97	8.6468	7.4534	16.506	9.5377	7.2383	8.1055	5.937	4.497	11.23
	p_b						Carbon emissions						Product recovery rate					
	112.55	113.73	114.68	114.4	115.15	123.65	8245.7	5766.8	6523.7	2643.1	2014.1	4441.1	0.6123	0.6063	0.6152	0.603	0.5992	0.6767
	112.61	113.78	114.59	114.44	115.18	123.73	9312.7	6648.6	7501.4	3621.7	2759.8	6092.6	0.612	0.6061	0.6143	0.6028	0.5991	0.6764
	112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
	112.7	113.85	114.45	114.51	115.23	123.84	10810.	7884.9	8885.3	4993.7	3805.2	8415.7	0.6115	0.6057	0.613	0.6025	0.5988	0.6758
	112.73	113.88	114.39	114.53	115.25	123.89	11355.	8334.3	9392.6	5492.4	4185.2	9262.6	0.6113	0.6056	0.6125	0.6023	0.5987	0.6756
	g						s_{r1}						s_{r2}					
l 26.4 24.2 22 19.8 17.6	49.63	53.1351	51.75	69.167	69.167	69.167	793.88	885.22	854.38	951.39	1008.41	790.51	793.4	885.79	854.93	947.95	1005.21	788.07
	49.623	53.1288	51.759	69.167	69.167	69.167	793.87	885.21	854.75	951.43	1008.43	791.08	793.39	885.79	855.3	947.99	1005.23	788.64
	49.618	53.1238	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
	49.613	53.1197	51.771	69.167	69.167	69.167	793.87	885.21	855.28	951.48	1008.46	791.88	793.39	885.78	855.83	948.04	1005.26	789.45
	49.61	53.1163	51.776	69.167	69.167	69.167	793.87	885.21	855.47	951.5	1008.47	792.18	793.39	885.78	856.02	948.06	1005.27	789.74
	ρ_1						ρ_2						ψ					
	14.868	12.993	14.312	9.3258	8.0679	17.86	13.744	11.876	13.133	8.8014	7.5864	16.815	12.231	9.2661	10.365	7.6056	5.7508	14.469
	14.867	12.993	14.296	9.3244	8.067	17.834	13.744	11.876	13.117	8.8001	7.5856	16.791	10.809	8.2005	9.1583	6.7353	5.0974	12.763
	14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
	14.867	12.992	14.273	9.3224	8.0658	17.798	13.744	11.876	13.095	8.7983	7.5844	16.756	8.7702	6.6671	7.4285	5.4809	4.1535	10.328
	14.867	12.992	14.264	9.3217	8.0653	17.785	13.744	11.876	13.087	8.7976	7.5839	16.744	8.0144	6.0971	6.7875	5.014	3.8016	9.4286
	p_b						Carbon emissions						Product recovery rate					
	111.38	112.87	113.43	113.7	114.62	122.27	10143.	7334.1	8287.5	4385.	3341.1	7400.8	0.6181	0.6107	0.619	0.6065	0.6019	0.6837
	112.1	113.4	114.03	114.13	114.95	123.12	10144.	7334.8	8276.7	4384.3	3340.8	7390.2	0.6145	0.608	0.616	0.6043	0.6002	0.6794
	112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
	113.11	114.17	114.9	114.76	115.42	124.34	10145.	7335.8	8261.3	4383.4	3340.3	7375.2	0.6094	0.6042	0.6116	0.6012	0.5979	0.6733
	113.49	114.45	115.22	114.99	115.6	124.79	10145.	7336.2	8255.7	4383.1	3340.1	7369.6	0.6075	0.6027	0.61	0.6	0.597	0.6711

Parameter with values	Changes in optimal values																	
	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS
	g						s_{r1}						s_{r2}					
δ 0.498 0.474 0.45 0.426 0.402	48.475	51.691	50.378	65.789	65.789	65.789	791.63	881.66	850.36	943.38	999.815	784.69	791.15	882.24	850.91	939.95	996.614	782.25
	49.051	52.415	51.076	67.478	67.478	67.478	792.74	883.42	852.67	947.34	1004.05	788.04	792.26	884.	853.22	943.91	1000.85	785.6
	49.618	53.124	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
	50.175	53.818	52.446	70.856	70.856	70.856	795.02	887.03	857.47	955.72	1013.	795.15	794.54	887.6	858.02	952.28	1009.8	792.71
	50.722	54.497	53.117	72.544	72.544	72.544	796.18	888.88	859.96	960.13	1017.71	798.91	795.7	889.45	860.5	956.69	1014.51	796.47
	ρ_1						ρ_2						ψ					
	14.707	12.84	14.19	9.2319	7.9874	17.655	13.591	11.731	13.016	8.7121	7.5097	16.62	9.5732	7.2641	8.1323	5.9827	4.5314	11.31
	14.787	12.916	14.236	9.2771	8.0264	17.734	13.667	11.803	13.061	8.755	7.5469	16.695	9.6279	7.309	8.1675	6.0128	4.554	11.363
	14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
	14.949	13.071	14.33	9.3707	8.1073	17.897	13.822	11.95	13.15	8.8443	7.6239	16.85	9.7399	7.4013	8.2394	6.0754	4.6011	11.473
	15.033	13.15	14.377	9.4192	8.1492	17.981	13.901	12.026	13.195	8.8905	7.6639	16.931	9.7972	7.4486	8.2763	6.1078	4.6256	11.53
	p_b						Carbon emissions						Product recovery rate					
	112.71	113.87	114.34	114.51	115.23	123.85	10220.	7426.8	8405.4	4690.2	3574.	7904.6	0.6114	0.6057	0.6123	0.6025	0.5988	0.6758
	112.69	113.85	114.42	114.49	115.22	123.82	10181.	7380.3	8336.4	4537.6	3457.7	7644.1	0.6116	0.6058	0.6129	0.6025	0.5989	0.6759
	112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
	112.63	113.8	114.61	114.46	115.2	123.76	10109.	7292.	8200.8	4228.8	3222.4	7117.7	0.6118	0.606	0.6142	0.6027	0.599	0.6762
	112.6	113.78	114.71	114.45	115.19	123.74	10075.	7250.2	8134.3	4072.5	3103.2	6851.5	0.612	0.6061	0.6149	0.6028	0.5991	0.6763
ζ 1.03 0.94 0.85 0.76 0.67	g						s_{r1}						s_{r2}					
	45.449	48.6752	48.245	90.278	90.278	90.278	990.2	1290.1	1261.7	1476.1	1645.05	1238.5	988.56	1289.9	1261.4	1471.9	1641.09	1235.2
	47.256	50.5792	49.791	77.083	77.083	77.083	875.69	1035.5	1005.9	1149.6	1243.59	955.14	874.72	1035.7	1006.1	1145.8	1240.06	952.37
	49.618	53.1238	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
	52.938	56.7358	54.42	63.889	63.889	63.889	732.68	786.35	756.01	817.76	854.06	685.13	732.58	787.17	756.81	814.61	851.117	682.94
	58.006	62.2078	58.185	60.119	60.119	60.119	685.49	716.83	686.44	721.21	744.938	610.47	685.69	717.85	687.44	718.3	742.209	608.48
	ρ_1						ρ_2						ψ					
	28.891	30.37	31.649	16.31	17.06	35.86	27.051	28.383	29.601	15.424	16.129	33.916	15.267	10.566	11.169	8.4246	5.8552	13.951
	20.712	19.443	20.741	12.219	11.391	24.49	19.289	18.001	19.237	11.546	10.743	23.111	12.232	8.9176	9.644	7.1181	5.192	12.627
	14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
	10.496	8.7483	10.012	7.1617	5.8805	13.421	9.5975	7.8484	9.0522	6.7481	5.5103	12.602	7.4512	5.8524	6.8107	5.11	3.9876	10.264
	7.1257	5.7632	6.9801	5.4852	4.3339	10.309	6.4008	5.0178	6.1773	5.1571	4.0433	9.6502	5.4497	4.4071	5.4538	4.2689	3.413	9.1459
	p_b						Carbon emissions						Product recovery rate					
	109.87	112.22	113.32	113.29	114.57	122.52	16696.	11199.	11755.	3005.5	2111.1	4438.5	0.6257	0.6139	0.6225	0.6086	0.6021	0.6824
	111.38	113.04	113.88	113.94	114.9	123.19	13169.	9224.9	9977.8	4170.1	3066.1	6593.9	0.6181	0.6098	0.6176	0.6053	0.6005	0.6791
	112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
	113.77	114.57	115.19	114.94	115.51	124.37	7452.4	5507.5	6596.3	4189.2	3284.4	7503.6	0.6061	0.6021	0.61	0.6003	0.5975	0.6732
	114.78	115.3	115.9	115.37	115.79	124.93	5017.2	3752.5	4957.3	3792.3	3042.8	7249.9	0.6011	0.5985	0.6068	0.5982	0.596	0.6704

Parameter with values	Changes in optimal values																	
	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS
	g						s_{r1}						s_{r2}					
η 0.436	50.978	54.4075	52.727	66.821	66.821	66.821	772.43	841.18	810.92	895.55	939.691	744.04	771.98	841.72	811.43	892.03	936.412	741.57
0.418	50.272	53.7425	52.232	67.949	67.949	67.949	782.99	862.32	832.1	922.51	972.699	766.82	782.53	862.88	832.63	919.03	969.46	764.36
0.4	49.618	53.1238	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
0.382	49.01	52.5467	51.326	70.486	70.486	70.486	805.08	910.07	879.98	982.63	1047.29	818.42	804.59	910.66	880.54	979.23	1044.13	816.
0.364	48.443	52.0071	50.911	71.92	71.92	71.92	816.64	937.17	907.16	1016.3	1089.66	847.82	816.13	937.78	907.74	1013.	1086.52	845.41
	ρ_1						ρ_2						ψ					
	13.336	11.107	12.389	8.6202	7.0954	15.863	12.284	10.072	11.293	8.1283	6.6565	14.906	8.6332	6.7471	7.6414	5.5746	4.3391	10.951
	14.09	12.012	13.299	8.9666	7.5615	16.8	13.003	10.938	12.164	8.4588	7.1023	15.802	9.1494	7.0498	7.9214	5.8055	4.4578	11.183
	14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
	15.668	14.058	15.351	9.691	8.6148	18.916	14.507	12.894	14.126	9.1498	8.1091	17.825	10.236	7.6621	8.4868	6.2897	4.6978	11.653
	16.493	15.219	16.515	10.07	9.2128	20.117	15.294	14.003	15.238	9.5114	8.6805	18.972	10.808	7.9719	8.7724	6.544	4.8193	11.892
	p_b						Carbon emissions						Product recovery rate					
	113.18	114.13	114.78	114.71	115.33	124.02	8882.2	6596.9	7595.6	4278.	3347.1	7489.3	0.6091	0.6044	0.6121	0.6014	0.5983	0.6749
	112.93	113.98	114.64	114.6	115.27	123.91	9503.6	6964.9	7931.2	4337.6	3349.4	7446.9	0.6104	0.6051	0.6128	0.602	0.5986	0.6755
	112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
	112.38	113.67	114.38	114.36	115.15	123.67	10805.	7708.1	8606.6	4414.3	3318.9	7291.3	0.6131	0.6067	0.6143	0.6032	0.5992	0.6766
	112.1	113.51	114.25	114.23	115.09	123.55	11486.	8083.4	8946.6	4425.9	3282.9	7171.7	0.6145	0.6074	0.6151	0.6039	0.5995	0.6772
	g						s_{r1}						s_{r2}					
λ 0.09	49.75	53.2951	51.929	69.167	69.167	69.167	791.49	881.73	851.3	949.94	1006.21	786.63	791.19	882.47	852.03	946.57	1003.09	784.38
0.825	49.689	53.2181	51.855	69.167	69.167	69.167	792.59	883.29	852.97	950.64	1007.21	788.82	792.21	883.95	853.62	947.24	1004.06	786.48
0.75	49.618	53.1238	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
0.675	49.537	53.0122	51.66	69.167	69.167	69.167	795.34	887.51	857.52	952.39	1009.93	794.76	794.76	887.99	857.97	948.91	1006.67	792.22
0.6	49.447	52.8833	51.537	69.167	69.167	69.167	797.01	890.21	860.43	953.45	1011.66	798.56	796.31	890.58	860.75	949.93	1008.35	795.89
	ρ_1						ρ_2						ψ					
	11.758	8.6097	9.4566	7.3706	5.3227	11.752	10.875	7.7813	8.5886	6.9614	4.9892	11.033	9.5705	7.2679	8.1038	5.9728	4.5225	11.276
	13.298	10.782	11.848	8.3377	6.6823	14.756	12.297	9.8113	10.827	7.872	6.2758	13.877	9.6226	7.3067	8.1482	6.0055	4.547	11.339
	14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
	16.47	15.25	16.771	10.33	9.4804	20.94	15.221	13.982	15.431	9.7453	8.9215	19.728	9.7533	7.4124	8.2691	6.0876	4.6137	11.511
	18.11	17.563	19.322	11.362	10.93	24.145	16.731	16.14	17.815	10.713	10.291	22.757	9.8326	7.48	8.3465	6.1373	4.6563	11.621
	p_b						Carbon emissions						Product recovery rate					
	112.71	113.87	114.57	114.51	115.24	123.86	10009.	7229.9	8148.1	4333.7	3301.2	7294.3	0.6114	0.6057	0.6134	0.6024	0.5988	0.6757
	112.69	113.85	114.55	114.5	115.23	123.83	10071.	7277.	8201.8	4356.8	3318.8	7333.5	0.6116	0.6058	0.6135	0.6025	0.5989	0.6758
	112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
	112.62	113.79	114.47	114.46	115.19	123.74	10228.	7405.3	8347.8	4414.8	3366.5	7439.9	0.6119	0.606	0.6137	0.6027	0.599	0.6763
	112.58	113.76	114.42	114.43	115.17	123.69	10323.	7487.3	8441.2	4450.	3397.1	7508.1	0.6121	0.6062	0.6139	0.6028	0.5991	0.6766

Parameter with values	Changes in optimal values																	
	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS	VN1	VN2	RCS	MS1	MS2	CS
	g						s_{r1}						s_{r2}					
μ 0.236 0.268 0.3 0.332 0.364	49.577	53.0297	51.676	69.167	69.167	69.167	794.56	887.11	857.09	951.9	1009.68	794.21	794.12	887.69	857.64	948.49	1006.47	791.76
	49.598	53.0783	51.723	69.167	69.167	69.167	794.22	886.12	856.03	951.68	1009.04	792.82	793.76	886.7	856.58	948.25	1005.83	790.38
	49.618	53.1238	51.766	69.167	69.167	69.167	793.87	885.21	855.05	951.46	1008.45	791.52	793.39	885.79	855.59	948.02	1005.25	789.09
	49.638	53.1661	51.806	69.167	69.167	69.167	793.53	884.37	854.14	951.24	1007.9	790.32	793.03	884.94	854.68	947.78	1004.7	787.9
	49.658	53.2053	51.843	69.167	69.167	69.167	793.18	883.59	853.3	951.02	1007.39	789.22	792.67	884.16	853.84	947.55	1004.2	786.8
	ρ_1						ρ_2						ψ					
	14.917	14.877	16.363	9.3564	9.2617	20.458	13.793	13.707	15.124	8.8301	8.7323	19.308	9.7183	7.4033	8.2587	6.0656	4.6079	11.496
	14.892	13.93	15.318	9.3398	8.6611	19.129	13.769	12.787	14.109	8.8146	8.1558	18.034	9.7008	7.3781	8.2299	6.0547	4.5921	11.455
	14.867	12.992	14.283	9.3233	8.0663	17.814	13.744	11.876	13.105	8.7991	7.5849	16.772	9.6834	7.3547	8.2032	6.0437	4.5773	11.417
	14.843	12.063	13.257	9.3068	7.4768	16.511	13.719	10.972	12.11	8.7837	7.0191	15.521	9.666	7.3331	8.1784	6.0328	4.5636	11.382
	14.818	11.141	12.24	9.2904	6.8922	15.218	13.695	10.076	11.123	8.7683	6.4581	14.282	9.6487	7.3132	8.1556	6.0219	4.5511	11.349
	p_b						Carbon emissions						Product recovery rate					
	112.64	113.8	114.48	114.47	115.2	123.75	10186.	7394.2	8335.2	4399.3	3362.4	7430.8	0.6118	0.606	0.6137	0.6027	0.599	0.6762
	112.65	113.81	114.5	114.47	115.2	123.77	10165.	7363.7	8300.5	4391.6	3351.1	7405.4	0.6118	0.6059	0.6136	0.6026	0.599	0.6761
	112.66	113.82	114.51	114.48	115.21	123.79	10144.	7335.3	8268.2	4383.8	3340.5	7381.9	0.6117	0.6059	0.6136	0.6026	0.5989	0.676
	112.67	113.83	114.53	114.48	115.22	123.81	10124.	7309.1	8238.3	4376.1	3330.7	7360.1	0.6117	0.6058	0.6135	0.6026	0.5989	0.676
	112.68	113.84	114.54	114.49	115.22	123.83	10103.	7284.9	8210.7	4368.4	3321.7	7340.	0.6116	0.6058	0.6135	0.6026	0.5989	0.6759