

Jauhari, Wakhid Ahmad; Niimas Ayu Frensilia Putri Adam; Rosyidi, Cucuk Nur; Pujawan, I. Nyoman; Shah, Nita H.

Article

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A closed-loop supply chain model with rework, waste disposal, and carbon emissions

Wakhid Ahmad Jauhari^{a,*}, Niimas Ayu Frensilia Putri Adam^a, Cucuk Nur Rosyidi^a,
I Nyoman Pujawan^b, Nita H. Shah^c

^a Department of Industrial Engineering, Universitas Sebelas Maret, Surakarta, Indonesia

^b Department of Industrial Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

^c Department of Mathematics, Gujarat University, Ahmedabad 380009, Gujarat, India

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ABSTRACT

This paper develops a closed-loop supply chain model consisting of a single manufacturer, single retailer, and single collector under various coordination scenarios. New products produced from the manufacturing and remanufacturing processes will be sold to the market at the same price. Used products collected by the collector are sorted so that products categorized as recoverable will be sold to the manufacturer. There are two recovery processes considered in this paper, namely remanufacturing and refurbishing. Used products below the minimum acceptable quality level of the manufacturer will be categorized as waste and will be disposed of. We assume that the manufacturing process is imperfect as it produces reworkable defective products. A carbon cap-and-trade policy and investment in green technologies are applied in order to restrict the carbon emissions generated by the production stage of the system. The demand at the market place depends on the green technology level, the quality of the product, and the selling price. The proposed model is constructed under five different scenarios – centralized, decentralized, and three Stackelberg games led, respectively, by the manufacturer, retailer, and collector. A numerical example is provided to illustrate and compare the proposed model under each scenario and investigate the sensitivity of some of the model parameters on the optimal solutions. The results show that the centralized scenario performs better in maximizing the total profit compared to the decentralized one. However, the retailer-led Stackelberg model tends to give more equitable profit to all players when the selling price is set at the lower level as this will attract more demand.

1. Introduction

In recent decades, the increasing awareness of environmental sustainability has encouraged many companies to implement closed-loop supply chains (CLSC). About 2.01 billion metric tons of municipal solid waste (MSW) are produced each year worldwide. By 2050, the total waste generated is expected to increase by 69.15%. Only 13.5% of today's waste is estimated to be recycled and only 5.5% can be composted [1]. Therefore, the circular economy, changing the pattern of 'taking-making-consuming-disposing' with a closed loop by combining several methods such as repair, remanufacturing, refurbishing, and recycling, has become the concern of the academic world and practice [2].

Besides contributing to energy saving and environmental sustainability, CLSC management also contributes to the economy [3]. Kodak, Xerox, Hewlett-Packard, Dell and Fuji Film are some of the companies that began to implement CLSC management due to its benefits long

before product take-back laws emerged [4,5]. A closed-loop supply chain integrates forward flows and reverse flows in the system. In the forward flows raw materials are manufactured into new products and then sold to the market, while in the reverse flows used products are collected and remanufactured into new versions of the original products [6].

As concerns about environmental protection grow, carbon emission has become an important issue in CLSC because it causes global warming. Global warming and environmental changes have threatened the sustainability of the world to a very dangerous level [7]. Therefore, efforts are needed from all parties to reduce the rate of increase in carbon emission levels in the earth's atmosphere. Carbon cap-and-trade has been the most popular policy adopted by regulators in many countries to control the emissions. This policy gives companies the flexibility to choose among different operational levels for compliance [8]. Companies can control the emissions by buying carbon permits if

* Corresponding author.

E-mail addresses: wachid_aj@yahoo.com (W.A. Jauhari), pujawan@ie.its.ac.id (I.N. Pujawan).

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their total carbon emissions exceed the cap or by selling extra carbon permits if their total carbon emissions are less than the cap [9].

Furthermore, the increase of low-carbon awareness considerably influences customer behavior. Customers are willing to pay a high price for eco-friendly products [10–12]. Motivated by this, more companies are willing to invest in adopting green technologies to curb the carbon emissions released from their production processes [13–16]. Marks and Spencer, Walmart and H&M were among the first companies to employ cleaner technologies to cut emissions [17,18].

In today's competitive environment, the operations in CLSC need to be efficiently managed. Decisions on how to recover the returned items and to deal with defective items are critical because they significantly affect the environmental performance of CLSC. A remanufacturing process is usually used to recover the returned items into new items [19–21]. Some scholars employed a refurbishing process to increase the quality of returned items and sold them to the secondary market [22,23]. Later, customers have also grown more concerned with the quality of products, which consequently forces companies to produce high quality products. In the real situation, the production system may be degraded and thus generate some defective items. These need to be reworked via a reworking process to increase their quality [24,25]. The manufacturing, recovery (remanufacturing and refurbishing) and reworking processes done by the manufacturer generate carbon emissions. The manufacturer's effort to invest in green technology will consequently reduce the emissions released from the mentioned processes.

Based on the description above, although considerable research on CLSC has been widely discussed in the literature, none has considered carbon reduction, green technology investment, imperfect production and two recovery processes. Thus, in considering this context, we want to answer the following questions:

- (1) How does CLSC perform under the five coordination scenarios?
- (2) What are the influences of green technology investment on CLSC coordination?

In an attempt to answer the above questions, in this study we propose a CLSC model composed of a manufacturer, a retailer and a collector, considering emission reduction and an imperfect manufacturing system. Carbon cap-and-trade regulation is applied to cut down the amount of emissions coming from the supply chain. Some aspects, such as emission reduction efforts, two recovery processes, waste disposal, used items collection and imperfect production, are investigated. By considering the mentioned aspects jointly, we believe that the model can be closer to representing the real problem. The model captures a detailed CLSC process and is solved analytically, thus its solution provides a feasible operational plan for all parties involved. In addition, by allowing the inclusion of imperfect production and two recovery processes we can observe how the green technology investment affects the carbon emissions resulting from each process. In general, this study contributes to the literature on CLSC models as follows:

- (1) We assume that remanufactured items will be as good as newly manufactured items. Unlike Maiti and Giri [20], we assume that not all of the used items can be remanufactured. Furthermore, we consider refurbishing as another recovery process. We assume that refurbished items are of lower quality than the original products. Thus, refurbished items will be sold in the secondary market at a cheaper price.
- (2) There are very few CLSC models that consider the reworking process on defective items. However, we assume that the initial production process may be imperfect because it produces a certain amount of defective items; in order for them to attain the same quality standard as good products, they have to go through a reworking process [24,25].

- (3) We investigate a closed-loop model by making an assumption that the used products which have not passed the acceptable quality standard for remanufacturing or refurbishing are considered as waste and need to be disposed of. The major difference between our model and the other studies mentioned above [19,20,24,25] is that we assume that the disposal process is performed by the collector. In addition, we also assume that, after receiving the recoverable products from the collector, the manufacturer performs an inspection process to sort them out.
- (4) We consider carbon cap-and-trade policy as an effort from an external party to curb the carbon emissions produced by the manufacturer. Also, we assume that the manufacturer has an option to invest in green technology in order to lessen the carbon emissions. Furthermore, the green technology level also affects the demand rate; that is, the green technology applied by the manufacturer induces more demand. Unlike Bai et al. [15], we consider the carbon emissions generated by each stage of production, such as manufacturing, remanufacturing, refurbishing, and reworking. We assume that each stage emits different carbon emissions.

The remainder of this paper is arranged as follows. Section 2 provides the literature review. Section 3 describes the proposed problem. The main notation and assumptions are defined in Section 4. Section 5 presents the development of the proposed model and analytical results are provided. A numerical example and sensitivity analysis are performed to demonstrate the feasibility of the results in Sections 6 and 7, respectively. Section 8 presents managerial insights. Finally, we conclude the paper with discussion and further research directions in Section 9.

2. Literature review

This research is closely related to five streams of literature: (1) considering third parties in the reverse channel; (2) refurbishing as an alternative to the recovery process; (3) waste disposal on used items; (4) imperfect production; and (5) green technology investment and carbon cap-and-trade policy. In the first stream, researchers have investigated the involvement of third-party companies as collectors of used items. Savaskan et al. [26] addressed the problem of determining the right reverse supply chain for collecting used items from customers in the CLSC. Then, Huang et al. [27] further extended Savaskan's research by assuming that retailers and third parties competitively collect used products. Maiti and Giri [20] also developed Savaskan's et al. [26] study by considering the third party as a single channel in the reverse supply chain. The retailer focused only on selling the product to the customer. Later, Giri et al. [28] proposed a CLSC model with two different channels. In the first channel, the retailer and e-tail (internet) sell the products to the customers and in the second channel, the collector and e-tail channel collect the used items to be remanufactured. The study presented by Taleizadeh et al. [29] is another example in this field, and investigates four different scenarios of the reverse channel of the CLSC, where the collection process is conducted by the integrated supply chain (centralized case), manufacturer, retailer, and third party respectively. Furthermore, the involvement of third parties then began to be widely used in research as recycling dealers or collectors [30–33].

The second stream focuses on alternative recovery processes for the used products. There are some types of recovery process that can be used to recover the used products, i.e. remanufacturing and refurbishing. Remanufacturing is a range of processes to restore a product to the specification of the original manufactured product using reused, repaired and new parts. For example, a used printer product is remanufactured by replacing the cartridge component that is no longer functioning with a new one. Refurbishing is a process to rebuild the used product to serve its original function. A smartphone is a common example of a refurbished product in the market. The used smartphone is

improved and fixed through the refurbishing process so that it functions like a new one. Because the quality of refurbished products is lower than remanufactured products, they are commonly sold to the secondary market at a lower price. Konstantaras et al. [22] proposed a CLSC system with a refurbishing process that produces a lower quality product and compared the results with new or remanufactured ones. The refurbished products are then sold at a lower price to the secondary market. Zhang et al. [34] determined the pricing strategies for a refurbished product in a supply chain system. It was found that when the refurbishing cost increases, the wholesale and retail prices of the brand-new products will decrease, and when the repair cost is low, the manufacturer and the retailer will get a double marginalization effect. Later, Li et al. [35] addressed the WEEE (Waste Electrical and Electronic Equipment) industry, involving a remanufacturer who remanufactured and refurbished returned items. Their study focused on the pricing decision regarding both the remanufacturing and refurbishing rates. Benkherouf et al. [36] studied inventory systems involving refurbishing to determine the order and remanufacturing quantities as well as the inventory levels of the used products. Jauhari et al. [37] also proposed a CLSC model where the manufacturer performs all the operations and management processes. Used items which cannot be returned to “as good as brand new” quality will be refurbished. The potential of the government's policy effort on investing in the refurbishing industry has been proposed by Chen and Chen [38]. They investigated China's market for recovered products, which typically consists of both refurbished and remanufactured products. Furthermore, Christy et al. [39] considered a pricing decision in a three-echelon system with refurbishing, remanufacturing and quality-dependent demand. The remanufacturing process produces good-as-new items which are sold to the primary market and the refurbishing process results in lower quality items that are sold to the secondary market.

Several researchers have considered the waste disposal cost in the supply chain, since not all used items can be recovered. In the third stream, we focused on applied waste disposal activities. Hasanov et al. [40] studied a CLSC model by taking into consideration the disposal cost, energy, and transportation cost. Dwicahyani et al. [41] considered waste disposal for unrecoverable returned items and a rework process for imperfect items in a CLSC consisting of a supplier, a manufacturer and a retailer. Wu and Wu [42] studied pricing strategies in a self-selection waste disposal mode in a closed-loop system. Kundu and Chakrabarti [43] proposed a reverse logistic model for a single-stage system with waste disposal and two different markets. The items that were not recoverable would be disposed of as waste after a sorting or disassembling process. Jaber et al. [44] proposed a mathematical model for a two-echelon system with production and remanufacturing. They used a consignment policy to coordinate a manufacturer and a retailer and utilized waste disposal for managing unrecoverable items.

Another stream of related literature studies imperfect production. Previous research considers the perfection of the manufacturing process. In reality, defective products are unavoidable for many reasons, such as displacement during the production process, machine defects, and other factors [24]. The reworking process can be carried out to improve the quality of defective products. The reworking process can be defined as the effort to reprocess or correct defective, failed or non-conforming products, through the use of original or alternate equivalent processing, in a manner that assures compliance of the product with specifications. In an electronics company, the reworking process is done to correct poor solder joints caused by faulty assembly or thermal cycling. Moshtagh and Taleizadeh [45] considered the existence of imperfect production processes that produce defective products. The defective product is then reworked to restore the quality to a level equal to the non-defective products. Recently, Taleizadeh and Moshtagh [46] extended their work by proposing a consignment stock scenario for a CLSC model considering defective items and the reworking process. They assumed that defective items are inevitable and may be produced by both the manufacturing and remanufacturing process. Jamal et al.

[47] also developed a deterministic CLSC model considering the reworking process as an alternative to restoring defective items to good items in a single production system. Giri and Sharma [24] analyzed a closed-loop supply chains model where the manufacturing process is assumed to be imperfect and the defective items are reworked with a return rate that is affected by the quality. They also considered a return rate based on the quality, as in the research by El Saadany and Jaber [48]. Later, Jauhari et al. [25] proposed a manufacturer–retailer closed-loop model with a learning and reworking process. They assumed that the imperfect items generated from regular production will be reworked.

The fifth stream deals with reducing carbon emissions through green technology investment and carbon policies. In reducing the carbon emissions, the regulations such as carbon cap-and-trade policy, has been extensively used by several researchers. In the regulation, government agencies give emissions allocation to a company (carbon cap), and companies can buy or sell the carbon deficits or residual carbon in carbon trading markets [15]. Furthermore, there is a significant growth of consumers motivated to buy eco-friendly products due to the increasing concern for the environment [11]. Shu et al. [49] examined the impacts of carbon cap and recovering decision on corporate social responsibility. Besides carbon cap-and-trade regulation, other policies that are also used by governments in an effort to reduce carbon emissions are low-carbon subsidies [50,51] and carbon tax [52,53]. Kundu and Chakrabarti [43] examined the impact of various carbon reduction policies on manufacturing-remanufacturing decisions. The results showed that carbon cap-and-trade policy is effective in curbing the carbon emissions produced by the manufacturer, and is also beneficial for firms, giving them an alternative choice of relaxing the carbon cap by buying carbon emissions from another firm. Taleizadeh et al. [54] studied pricing and logistic decisions in a multi-echelon CLSC, taking into account discounts on returned products and social and environmental aspects. Afterwards, Taleizadeh et al. [55] considered carbon cap-and-trade and technology investment to cut down the emissions released from the system. Bai et al. [15] examined the influence of carbon emission reduction on supply chain coordination by using carbon cap-and-trade regulation. In the model, manufacturers are assumed to invest in green technology in an effort to reduce carbon emissions. The customer demands are also dependent on the green technology level invested in by the manufacturer. Bai et al. [16] extended their previous model by investigating the influence of risk aversion and green technology investment on coordinating a supply chain involving a manufacturer and a retailer. Two coordination policies, manufacturer-led policy and centralized policy, are proposed and compared to show that the performance of the investigated supply chain can be improved by the adoption of green technology. A similar approach was also taken by Li et al. [51], who considered carbon emission level-dependent market demands. Jamali and Barzoki [56] proposed a competitive sustainable supply chain model where two manufacturers will reduce their carbon emissions by using green transportation outsourced to third parties in order to transport their products to the same retailer. Furthermore, Hasanov et al. [57] proposed a four-level CLSC addressing the energy usage, emissions and the disassembly process of returned items. Table 1 summarizes the differences between the proposed model and the previously published models.

3. Problem description

In this paper, we consider a closed-loop supply chain (CLSC) system that involves a manufacturer, a retailer, and a collector, taking into account waste disposal and carbon emissions. This system consists of two channel flows, forward and reverse. The forward supply chain involves a manufacturer and a retailer, where the manufacturer will produce the product and sell it to the customers through the retailer. Then, in the reverse supply chain, a collector will buy back the used

Table 1
A comparison of the proposed model with some related published research.

Papers	Demand	Recovery process	Collection effort investment	Quality improvement	Waste disposal	Rework consideration	Carbon emission	Logistical consideration
Maiti and Giri [20]	Price and quality dependent demand	Remanufacturing	Yes	Manufacturing, Remanufacturing	No	No	No	No
Moshagh et al. [45]	Deterministic Green technology level, selling price, and quality dependent demand	Remanufacturing and refurbishing	No	No	Yes	Yes	No	Yes
Bai et al. [15]	Deterministic	Remanufacturing	No	No	No	No	Carbon cap-and-trade policy	Yes
Jauhari et al. [25]	Deterministic	Remanufacturing	No	No	No	Yes	No	Yes
Giri and Sharma [24]	Deterministic	Remanufacturing	No	No	No	Yes	No	Yes
Kundu and Chakrabarti [43]	Deterministic	Remanufacturing	No	No	Yes	No	Carbon tax, strict carbon cap, and carbon cap-and-trade	Yes
Li et al. [51]	Retail price and carbon emission reduction level	Remanufacturing	No	No	No	No	Low-carbon CLSC	No
Konstantaras et al. [22]	Deterministic	Remanufacturing and refurbishing	No	No	No	No	No	Yes
Zerang et al. [33]	Selling price and market-dependent demand	Remanufacturing	Yes	No	No	No	No	No
Taleizadeh et al. [32]	Sale price, quality of the product, buy-back price, sales effort, and reference price dependent demand	Remanufacturing	Yes	Manufacturing, Remanufacturing	No	No	No	No
This paper	Green technology level, selling price, and quality dependent demand	Remanufacturing and refurbishing	Yes	Manufacturing, Remanufacturing, Refurbishing	Yes	Yes	Carbon cap-and-trade policy	No

products from the customer. The used products categorized as recoverable will be sold to the manufacturer and the unrecoverable products will be disposed of. A lead acid battery is a real example that can clearly represent the product return process. After the batteries are used by customers for a certain period and their function has decreased, or after their end of life, consumers will want to replace them with new ones. Although not all customers are willing to return the used batteries, some of them agree to return them to the collection point owned by the collector. In some cases, the battery shop that sells the vehicle batteries may have a good relationship with a collector. Customers who purchase vehicle batteries in that shop may agree to return their used batteries to it. Then, the used batteries collected by the shop will be sent to the collector. However, in this research we simplify the product return process and assume that the collector can get the used product directly from some customers. The manufacturer will inspect the used products carefully and classify them into two categories, remanufacturable or refurbishable items. The remanufactured products are then sold to the primary market along with new products produced by the regular manufacturing process. On the other hand, if the quality of the used products is lower than the minimum standard of remanufacturing, they will be recovered by the refurbishing process. Refurbishing is a less thorough process than remanufacturing and the items that are refurbished are assumed to be of lower quality and will be sold to the secondary market at a lower price (see Fig. 1).

The remanufacturing and refurbishing processes are assumed to be perfect. Thus, these processes always generate non-defective items. The manufacturing process is imperfect due to a number of factors, such as deterioration of the production process, wear of machinery, or low quality raw materials. Therefore, it generates some defective products which cannot be ignored in the production process. The defective products are then reworked in the reworking process and the reworked products are assumed to be of the same good quality as manufactured products.

In this system, the manufacturer invests in green technologies in order to reduce carbon emissions under cap-and-trade regulations in which the government agency allocates to a firm a specific pre-determined capacity limit of carbon emissions as a result of its industrial activities. If the level of the emissions produced by the firm is higher than the allocated permits, a penalty is applied for each unit of the extra emission. On the other hand, a firm that reduces its emission and produces less than the allowed capacity can sell or trade the unused amounts to other companies in a carbon trading market. In addition, the collector also has a chance to invest in order to increase the returned products.

4. Notation and assumptions

The notation used in this research is as follows:
Input parameters for the manufacturer

- ρ proportion of remanufacturable items, $0 \leq \rho < 1$
- f proportion of defective items of end products from the manufacturing process, $0 \leq f < 1$
- C_M manufacturing cost, (in \$)
- C_S raw material cost, (in \$)
- C_{REM} remanufacturing cost, (in \$)
- C_{REF} refurbishing cost, (in \$)
- C_{IM} inspection cost for recoverable items, (in \$)
- C_{RW} reworking cost, (in \$)
- C_{insp} inspection cost for manufactured end products, (in \$)
- C_q quality improvement cost of the manufacturer, (in \$)
- P_{2nd} wholesale price for the secondary market, (in \$)
- Q_r quality level of remanufacturable products, (in units)
- Q_f quality level of refurbishable products, (in units)

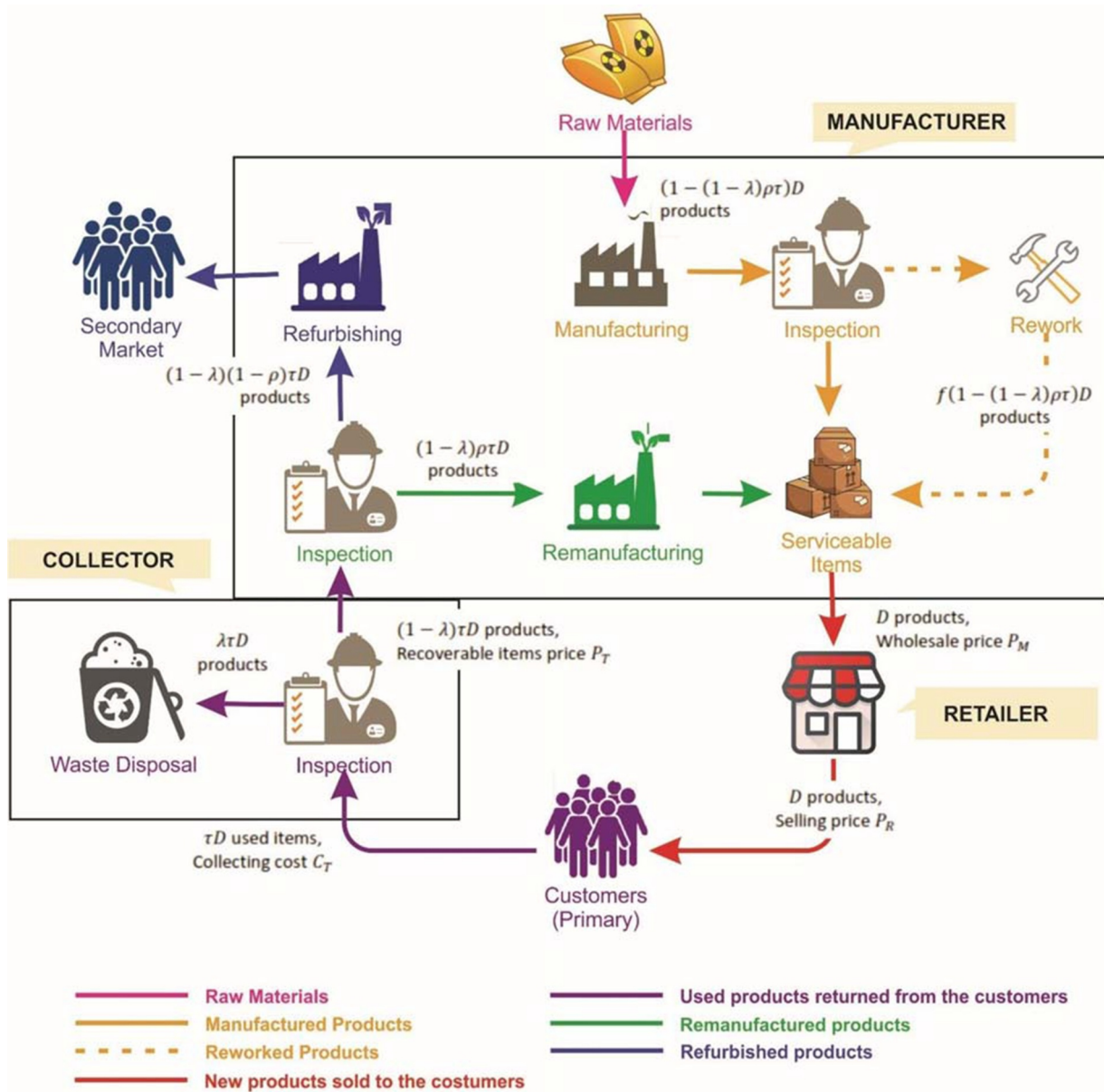


Fig. 1. Graphical representation of the proposed CLSC system.

Q_s	quality level of products sold to the secondary market, (in units)	b_2	parameter of the green technology effect on lessening carbon emissions generated from the remanufacturing process, $0 \leq b_2 < 0$
C	carbon cap	b_3	parameter of the green technology effect on lessening carbon emissions generated from the refurbishing process, $0 \leq b_3 < 0$
C_p	trading price of carbon emission permits, (in \$)	b_4	parameter of the green technology effect on lessening carbon emissions generated from the reworking process, $0 \leq b_4 < 0$
η	investment made by the manufacturer for adopting green technology, ($\eta > 0$)	$\Pi_M(s, P_M, Q)$	total profit of the manufacturer
$E_m(s)$	total emission generated from the supply chain	<i>Input parameters for the retailer</i>	
e_1	carbon emissions per unit in the manufacturing process when the green technology level is zero	D	demand rate, (in units)
e_2	carbon emissions per unit in the remanufacturing process when the green technology level is zero	d	basic demand, (in units)
e_3	carbon emissions per unit in the refurbishing process when the green technology level is zero	α	sensitivity factor of green technology in the demand, $0 \leq \alpha < 1$
e_4	carbon emissions per unit in the reworking process when the green technology level is zero	β	sensitivity factor of selling price in the demand, $0 \leq \beta < 1$
b_1	parameter of the green technology effect on lessening carbon emissions generated from the manufacturing process, $0 \leq b_1 < 0$	γ	sensitivity factor of quality in the demand, $0 \leq \gamma < 1$
		$\Pi_R(P_R)$	total profit earned by the retailer, (in \$)

Input parameters for the collector

- λ proportion of unrecoverable items among returned products, $0 \leq \lambda < 1$
- C_T recycling cost for used items, (in \$)
- C_{IT} inspection cost for used items, (in \$)
- C_{WD} waste disposal cost, (in \$)
- P_T selling price of the recoverable items, (in \$)
- g investment made by the collector to collect returned products
- $\Pi_C(\tau)$ total profit earned by the collector, (in \$)

For the whole system

- $\Pi_C(s, P_R, Q, \tau)$ joint total profit earned by the whole system under centralized scenario

Decision variables

- s green technology level
- Q quality level of end products, (in units)
- P_M unit wholesale price, (in \$)
- P_R unit selling price, (in \$)
- τ collection rate of used items by the collector, $0 \leq \tau < 1$

The following assumptions are needed to develop the proposed model:

- (1) The increase of customers' environmental awareness influences their purchasing behaviors. Customers are willing to buy green (low-carbon) products with a high price [10]. For this reason, the manufacturer can invest in a green technology to lessen the emissions. Following the existing literature, e.g. Bai et al. [15,16], we formulate the market demand in the single selling period, which depends on the green technology level, the retailer's selling price, and the quality of the product and is defined as $D = d + \alpha s - \beta P_R + \gamma Q$. In this study, a green technology level represents the capability of the technology used by the manufacturer to reduce the emissions. This assumption is based on the fact that customers may obtain information about the green technology from promotional efforts by the manufacturers. In reality, manufacturers often promote their products to customers by giving specific information about their green practices.
- (2) Not all of the used products can be collected by collectors. The collection rate of the collector (τ) is only a fraction of the total demand and returned products that have not passed the acceptable quality level will be disposed of. This assumption is commonly used in the literature (e.g. Kundu and Chakrabarti [43], El Saadany and Jaber [48], Taleizadeh et al. [55]).
- (3) The cost of remanufacturing the used items is lower than the cost of manufacturing new products, but higher than the cost of refurbishing ($C_M > C_{REM} > C_{REF}$) [37, 39].
- (4) The returned products are acceptable for the remanufacturing process if they conform with the minimum quality Q_r or attained minimum quality Q_f for the refurbishing process. However, after the remanufacturing process the quality of the remanufactured items becomes Q and after the refurbishing process the quality of the refurbished items becomes Q_s . The refurbished products have lower quality than the newly manufactured or remanufactured products. We take $Q > Q_s > Q_r > Q_f > 0$ [39].
- (5) The remanufactured products and newly manufactured products will be sold to the primary market at the same price (P_M) and the refurbished products will be sold to the secondary market with lower price P_{2nd} . We assume that $P_M > P_{2nd} > 0$ [36,37].
- (6) The manufacturing process is imperfect, so it produces some defective products [47,58].
- (7) All defective products can be repaired and all of the reworked products attain the same quality as a non-defective product [25,41,53,59].
- (8) The manufacturer has an opportunity to make an investment in green technologies to cut down the emissions released from the processes, which finally leads to an increase of market share. To derive the green technology investment, we refer to the function

used by Bai et al. [15,16]. The investment can be realized by buying new equipment that can be used to reduce energy consumption or purchasing new technology that can be utilized to capture the carbon.

- (9) A collector can invest in collection efforts to increase the number of returned items. Following Maiti and Giri [20], the investment form is expressed as a quadratic function of the collection rate. The investment can be realized by conducting a promotion to induce the customer to return the used items.

5. Model formulation and analysis

The manufacturer sells D products to the retailer at the wholesale price P_M . The customers buy the products from the retailer at a retailer price P_R . At the reverse, the collector collects τD products from customers at the collecting cost C_T . Then, after some inspection, $\lambda \tau D$ products must go through the waste disposal process because they do not meet the minimum quality standard for the recovery process of the manufacturer. From $(1 - \lambda)\tau D$ products that are sent to the manufacturer at the recoverable item price P_T , only $(1 - \lambda)\rho\tau D$ products are remanufacturable, and the rest $(1 - \lambda)(1 - \rho)\tau D$ of the products will be refurbished and sold to the secondary market at a lower price P_{2nd} . To satisfy demand D , the amount of $(1 - (1 - \lambda)\rho\tau)D$ products are produced via the manufacturing process. The manufacturing process is imperfect, thus generating $f(1 - (1 - \lambda)\rho\tau)$ defective products which finally should be fixed via the reworking process. Investment in quality improvement is conducted by the manufacturer. The investment for quality follows the quadratic cost function expressed as $C_q Q^2$ for the manufacturing process, $C_q(Q^2 - Q_r^2)$ for remanufacturing, and $C_q(Q_s^2 - Q_f^2)$ for the refurbishing process. The quadratic cost function has also been used by some researchers, including Chao et al. [60] and Li et al. [61] to express the quality investment.

Throughout the production stage, we assume that each process generates carbon emissions e . In order to control the carbon emissions, the manufacturer will invest in green technology s to reduce the carbon emissions. The quadratic functional form is used to represent the investment, which indicates that it is harder to provide the succeeding green technology level than the preceding one. The investment in green technologies is defined as follows:

$$INV_{GT} = \frac{1}{2}\eta s^2 \tag{1}$$

Eq. (2) represents the total emissions generated from the manufacturer's system, which are equal to the sum of emissions released from the manufacturing, remanufacturing, refurbishing, and reworking processes. The emissions released from each process are obtained by multiplying the emissions per unit product with the number of products processed in each process.

$$E_m(s) = (e_1 - b_1s)(1 - (1 - \lambda)\rho\tau)D + (e_2 - b_2s)(1 - \lambda)\rho\tau D + (e_3 - b_3s)f(1 - (1 - \lambda)\rho\tau)D + (e_4 - b_4s)(1 - \lambda)(1 - \rho)\tau D \tag{2}$$

The total amount of emissions $Em(s)$ is limited by the carbon cap allocated to the manufacturer C . When the total emissions exceed the carbon cap, then the manufacturer needs to buy carbon as the amount of shortfall from another company. On the other hand, if $Em(s)$ is less than C he can sell the excess and increase the profit. The cost (profit) incurred by the manufacturer associated with the carbon cap-and-trade policy is expressed as follows:

$$TC_{CCT} = C_p [E_m(s) - C] \tag{3}$$

The total cost of the manufacturing process consists of the manufacturing cost, raw material cost, inspection cost and quality improvement cost, given by the following equation:

$$TC_{Manf} = (1 - (1 - \lambda)\rho\tau)D(C_M + C_S + C_{insp} + C_q Q^2) \tag{4}$$

The total cost of the remanufacturing process can be calculated by summing up the remanufacturing cost and quality improvement cost of remanufacturing. The total cost of the remanufacturing process is presented as follows:

$$TC_{Rem} = (1 - \lambda)\rho\tau D(C_{REM} + C_q(Q^2 - Q_r^2)) \quad (5)$$

Eq. (6) expresses the total cost of the refurbishing process which is equal to the refurbishing cost and quality improvement cost for the refurbishing.

$$TC_{Ref} = (1 - \lambda)(1 - \rho)\tau D(C_{REF} + C_q(Q_s^2 - Q_f^2)) \quad (6)$$

To obtain the recoverable items, the manufacturer must pay P_T for each item. In addition, an inspection process is conducted to categorize the quality of recoverable items. The manufacturer will incur C_{IM} for each item screened in the inspection process. Therefore, the total cost incurred by the manufacturer for obtaining recoverable items is expressed by the following equation:

$$TC_{Rec} = (1 - \lambda)\tau D(P_T + C_{IM}) \quad (7)$$

As described in the above section, the manufacturing process includes some flawed production and generates some defective items. The reworking process is employed to increase the quality of defective items. The total cost of the reworking process can be calculated by multiplying the rework cost per unit item and the number of defective items resulting from the manufacturing process, which is

$$TC_{Rework} = f(1 - (1 - \lambda)\rho\tau)DC_{rw} \quad (8)$$

The manufacturer will sell the new products resulting from the manufacturing process and remanufactured products to the primary market. In addition, the refurbished products, of lower quality, will be sold to the secondary market at a cheaper price. Thus, the revenue for remanufacturing is given by the following expression:

$$RV_M = fDP_M + (1 - \lambda)(1 - \rho)\tau DP_{2nd} \quad (9)$$

The profit charged by the manufacturer under the carbon cap-and-trade regulation includes sales revenue, manufacturing cost, remanufacturing cost, refurbishing cost, used item collection cost, reworking cost, green technology investment cost, and revenue (cost) from buying or selling the extra carbon emission permits, and is expressed by

$$\begin{aligned} \Pi_M(s, P_M, Q) &= DP_M - (1 - (1 - \lambda)\rho\tau)D(C_M + C_s + C_{insp} + C_q Q^2) \\ &\quad - (1 - \lambda)\rho\tau D(C_{REM} + C_q(Q^2 - Q_r^2)) \\ &\quad - (1 - \lambda)(1 - \rho)\tau D(C_{REF} + C_q(Q_s^2 - Q_f^2) - P_{2nd}) \\ &\quad - (1 - \lambda)\tau D(P_T + C_{IM}) - f(1 - (1 - \lambda)\rho\tau)DC_{rw} - \frac{1}{2}\eta s^2 \\ &\quad - C_p[E_m(s) - C] \end{aligned} \quad (10)$$

The retailer total profit consists of the total revenue of the retailer and purchasing cost of the products from the manufacturer, which is formulated as follows:

$$\Pi_R(P_R) = DP_R - DP_M \quad (11)$$

As described in the above section, the collector collects used items from customers and incurs a recycling cost, C_T , for each collected item. The inspection cost, C_{IT} , is incurred by the collector for each item screened during the inspection process. The recycling cost and inspection cost of the collector are given by

$$TC_{Collect} = \tau D(C_T + C_{IT}) \quad (12)$$

The used items which are categorized as unrecoverable items will be disposed of. The total disposal cost of the collector can be determined by considering the number of items disposed of and the cost of

disposing of them, which is expressed as follows:

$$TC_{Disposal} = \lambda\tau DC_{wd} \quad (13)$$

The investment in collection efforts is also considered to increase the number of returns. The collection effort investment is assumed to be an increasing convex function of g , and is defined as a quadratic cost function expressed as follows:

$$INV_{CE} = \frac{1}{2}g\tau^2 \quad (14)$$

Therefore, the total profit of the collector, which consists of the total revenue of the collector, the collection cost of used items, and the investment cost in collecting used items, is given by

$$\Pi_C(\tau) = (1 - \lambda)\tau DP_T - \tau D(C_T + C_{IT}) - \lambda\tau DC_{wd} - \frac{1}{2}g\tau^2 \quad (15)$$

5.1. Centralized scenario

In the centralized scenario, all members of the supply chain are integrated as a whole system and cooperatively decide the green technology level, selling price, and product quality and collection rate. The total profit function of the investigated CLSC is given by

$$\begin{aligned} \Pi(s^C, P_R^C, Q^C, \tau^C) &= CC_p + P_R^C(d + \alpha s^C - \beta P_R^C + \gamma Q^C) - \frac{s^{C2}\eta}{2} \\ &\quad - \Omega_1(d + \alpha s^C - \beta P_R^C + \gamma Q^C)\tau^C - \frac{g\tau^2}{2} \\ &\quad + (d + \alpha s^C - \beta P_R^C + \gamma Q^C) \\ &\quad (s\phi_4 - C_q Q^{C2} - \phi_3 - (\lambda - 1) \\ &\quad (s^C\phi_1 - \phi_5 + (\phi_2 + C_p\phi_6 - C_p s^C\phi_7)\rho)\tau) \end{aligned} \quad (16)$$

where $0 < \tau^C < 1$ and $0 < Q^C < 1$.

Corollary 1. In the centralized scenario, if conditions (17) and (18) are satisfied, then the optimal solutions for the proposed problem can be realized.

$$\beta < \frac{\beta(2(d + \alpha s + 2Q\gamma)\eta - \alpha^2(d + \alpha s + Q\gamma) - 2\beta^2\eta P_R + 2Y(d + \alpha s - \beta P_R + \gamma Q)\alpha\tau + \alpha^2 P_R)}{(d + \alpha s - \beta P_R + \gamma Q)(Y^2\beta\tau^2 + 2\alpha\phi_4 - 2Y\beta\tau\phi_4 + \beta\phi_4^2)} \quad (17)$$

and

$$\begin{aligned} &- 4Y^2(d + \alpha s - \beta P_R + \gamma Q)^3 C_q \beta - g(\gamma - 2C_q Q\beta)^2 \eta \\ &\quad - 2(d + \alpha s - \beta P_R + \gamma Q)C_q(g\alpha^2 - 2g\beta(\eta + Y\alpha\tau - \alpha\phi_4) + \beta^2 \\ &\quad (g(\phi_4 - Y\tau)^2 + \eta(Ys + \Omega_1 - X)^2)) \\ &\quad > Y(d + \alpha s - \beta P_R + \gamma Q)^2(Y\gamma^2 + 4\beta C_q(X\alpha - Y(s\alpha + Q\gamma) - \alpha\Omega_1) + 4 \\ &\quad \beta^2 C_q(YQ^2 C_q + (Y\tau - \phi_4)(Ys + \Omega_1 - X))) \end{aligned} \quad (18)$$

Proof. See Appendix A.

To ensure $0 < \tau^C < 1$, we consider the following condition:

$$g > (\Omega_1 - X + sY)\beta P_R - (X - \Omega_1 - sY)(d + \alpha s + \gamma Q) \quad (19)$$

Also, to ensure $0 < Q^C < 1$, we consider the following condition:

$$\begin{aligned} 3C_q\gamma > \sqrt{C_q(C_q(d + \alpha s - \beta P_R)^2 + 3\gamma^2(-(\Omega_1 - X + sY)\tau + P_R - \phi_3 + s\phi_4))} \\ - C_q(d + \alpha s - \beta P_R) \end{aligned} \quad (20)$$

The values of Ω_1 , ϕ_3 and ϕ_4 are shown in Appendix A.

For searching the optimal solutions, the first-order necessary conditions $\frac{\partial \Pi_C}{\partial s^C} = 0$, $\frac{\partial \Pi_C}{\partial Q^C} = 0$, $\frac{\partial \Pi_C}{\partial P_R^C} = 0$, and $\frac{\partial \Pi_C}{\partial \tau^C} = 0$ must be satisfied. By rearranging the formulations, we find the expressions presented in Proposition 1.

Proposition 1. The equilibrium of each player decision variables is obtained in Eqs. (21), (22), (23), and (24), respectively.

$$P_R^M = \frac{d + s^M\alpha + Q^M\gamma + \beta P_M^M}{2\beta} \tag{26}$$

$$s^C = \frac{(CqQC^2 + \phi_3 - P_R^C)\alpha - \phi_4(d - \beta P_R^C + \gamma Q^C) + (\Omega_1\alpha + d(\lambda - 1)(\phi_1 - C_p\phi_7\rho) - (\lambda - 1)(\phi_5 - \alpha - (\phi_2 + C_p\phi_6)\alpha\rho + (\beta P_R^C - \gamma Q^C)(\phi_1 - C_p\phi_7\rho)))\tau}{2\phi_4\alpha - \eta - 2\alpha(\lambda - 1)(\phi_1 - C_p\phi_7\rho)\tau} \tag{21}$$

5.2.2. The collector's reaction

By taking into account the retailer's reaction, we can derive the collector's best reaction from the first-order condition.

$$Q^C = \frac{1}{3C_q\gamma} (\sqrt{(C_q(C_q(d + s^N\alpha - P_R^N\beta)^2 + 3\gamma^2(P_M^N - \phi_3 + s\phi_4 - (\lambda - 1)(s^N\phi_1 - \phi_5 + (\phi_2 + C_p\phi_6 - C_p s^N\phi_7)\rho)\tau^N))) - C_q(d + s^N\alpha - P_R^N\beta)}) \tag{22}$$

$$P_R^C = \frac{1}{2\beta} (d + \alpha s^C + CqQC^2\beta + \phi_3\beta - s^C\phi_4\beta + Q^C\gamma + \beta(\Omega_1 + (\lambda - 1)(s^C\phi_1 - \phi_5 + (\phi_2 + C_p\phi_6 - C_p s^C\phi_7)\rho))\tau) \tag{23}$$

$$\tau^C = \frac{(P_R^C\beta - d - s^C\alpha - Q^C\gamma)(\Omega_1 + (\lambda - 1)(s^C\phi_1 - \phi_5 + (\phi_2 + C_p(\phi_6 - s\phi_7))\rho))}{g} \tag{24}$$

Also, by substituting the optimal solution into Eq. (16), the optimal value of the total profit can be obtained.

$$\frac{\partial \Pi_c}{\partial \tau^M} = \Omega_1 \left(\frac{1}{2} (d + s^M\alpha + P_M^M\beta + Q^M\gamma) - d - s^M\alpha - Q^M\gamma \right) - g\tau = 0 \tag{27}$$

5.2. Manufacturer-led decentralized scenario

Here, the manufacturer acts as the leader who has control over the system, and the other players (retailer and collector) act as the followers. In this scenario, the retailer determines the selling price, P_R , and the collector determines the collection rate, τ . Then the manufacturer decides the green technology level, s , the quality of the product, Q , and the manufacturer's price, P_M by taking into consideration the best reaction of both members.

Corollary 3. When conditions (28) and (29) are satisfied, the profit function Π_c is concave in τ , then we can find the optimal solutions for the optimization problem of the collector.

$$-g < 0 \tag{28}$$

$$g > (\beta P_R - d - \alpha s - \gamma Q)\Omega_1 \tag{29}$$

5.2.1. The retailer's reaction

First, we obtain the best reactions of the retailer as a function of decisions s , Q , and P_M made by the manufacturer.

$$\frac{\partial \Pi_R}{\partial P_R^M} = d + s^M\alpha + Q^M\gamma + \beta P_M^M - 2\beta P_R^M = 0 \tag{25}$$

Proof. See Appendix C.

Thus, the optimal value of the collection rate is obtained by setting $\frac{\partial \Pi_c}{\partial \tau^M} = 0$ and, solving with respect to τ^M , we can derive the function presented in Proposition 3.

Corollary 2. If condition $-2\beta < 0$ is satisfied, the optimal solutions for the retailer's optimization problem can be obtained.

Proposition 3. The optimal reaction of the collector in manufacturer-led Stackelberg game is presented in Eq. (30).

$$\tau^M = \frac{\Omega_1(P_M^M\beta - d - s^M\alpha - Q^M\gamma)}{2g} \tag{30}$$

Proof. See Appendix B.

Therefore, by solving the first-order condition of Eq. (25) with respect to P_R , setting it equal to zero, this leads to the optimal reaction given in Proposition 2.

5.2.3. The manufacturer's optimal decision

After the reactions of the retailer and the collector can be known, the manufacturer takes both reactions into consideration and determines optimal decisions to maximize his own profit by solving the following equations:

Proposition 2. The optimal reaction of the retailer in manufacturer-led Stackelberg game is presented in Eq. (26).

$$\frac{\partial \Pi_M}{\partial s^M} = \frac{1}{4} \left(2\alpha \left(P_M^M - C_q Q^M - \phi_3 + s\phi_4 + \frac{\Omega_1(d + s^M\alpha - P_M^M\beta + Q^M\gamma)(\lambda - 1)(s^M\phi_1 - \phi_5 + (\phi_2 + C_p(\phi_6 - s^M\phi_7))\rho)}{2g} \right) - 4s^M\eta + \frac{1}{g} (d + s^M\alpha - P_M^M\beta + Q^M\gamma) \left(2g\phi_4 + \Omega_1(\lambda - 1) \left(2s^M\phi_1\alpha - \phi_5\alpha - P_M^M\phi_1\beta + Q\phi_1\gamma + \phi_2\alpha\rho + C_p(\phi_6\alpha + \phi_7(-2s^M\alpha + P_M^M\beta - Q^M\gamma))\rho + d(\phi_1 - C_p\phi_7\rho) \right) \right) \right) = 0 \tag{31}$$

$$\frac{\partial \Pi_M}{\partial P_M^M} = \left(d + s^M \alpha + Q^M \gamma + \frac{1}{2}(-d - s^M \alpha - P_M^M \beta - Q\gamma) \right) \left(1 - \frac{\Omega_1 \beta (\lambda - 1)(s^M \phi_1 - \phi_5 + (\phi_2 + C_p \phi_6 - C_p s^M \phi_7) \rho)}{2g} \right) - \frac{1}{2} \beta \left(P_M^M - C_q Q^{M2} - \phi_3 + s^M \phi_4 + \frac{\Omega_1 (d + s^M \alpha - P_M^M \beta + Q^M \gamma) (\lambda - 1)(s^M \phi_1 - \phi_5 + (\phi_2 + C_p \phi_6 - C_p s^M \phi_7) \rho)}{2g} \right) = 0 \tag{32}$$

$$\frac{\partial \Pi_M}{\partial Q^M} = \left(d + s^M \alpha + Q^M \gamma + \frac{1}{2}(-d - s^M \alpha - P_M^M \beta - Q^M \gamma) \right) \left(\frac{\Omega_1 \gamma (\lambda - 1)(s^M \phi_1 - \phi_5 + (\phi_2 + C_p \phi_6 - C_p s^M \phi_7) \rho)}{2g} - 2C_q Q^M \right) \frac{1}{2} \gamma \left(P_M^M - C_q Q^{M2} - \phi_3 + s^M \phi_4 + \frac{\Omega_1 (d + s^M \alpha - P_M^M \beta + Q^M \gamma) (\lambda - 1)(s^M \phi_1 - \phi_5 + (\phi_2 + C_p \phi_6 - C_p s^M \phi_7) \rho)}{2g} \right) = 0 \tag{33}$$

Corollary 4. When the condition (34) is satisfied, the profit function Π_M is concave in s , Q , and P_M , then we can find the optimal solutions for the optimization problem of the collector.

5.3.1. The collector's reaction

First, we obtain the best reactions of the collector as a function of decision P_R made by the retailer:

$$C_q > \max \left\{ -\frac{\gamma^2 \eta}{2\alpha^2 (d + s\alpha - P_R \beta + Q\gamma)}, \frac{\sqrt{C_q (C_q (d + s\alpha - P_R \beta)^2 + 3\gamma^2 (P_M - \phi_3 + s\phi_4 - (X + sY)\tau)) - C_q (d + s\alpha - P_R \beta)}}{3\gamma} \right\} \tag{34}$$

Proof. See Appendix D.

By setting the first-order conditions to zero, the manufacturer's reaction can be determined by the expressions presented in Proposition 4.

Proposition 4. The optimum manufacturer's variables, including green technology levels (s), wholesale price (P_M), and quality of the product (Q) are given in Eqs. (35), (36), and (37), respectively.

$$\frac{\partial \Pi_R}{\partial \tau^R} \equiv \Omega_1 (P_R^R \beta - Q^R \gamma - d - s^R \alpha) - g \tau^R = 0 \tag{38}$$

Corollary 5. When conditions (39) and (40) are satisfied, the profit function Π_c is concave in τ , then we obtain the optimal solutions for the optimization problem of the collector.

$$s^M = \frac{2g(\phi_4 \alpha - \eta) + 2d\Omega_1 \alpha (\lambda - 1)(\phi_1 - C_p \phi_7 \rho) - \Omega_1 \alpha (\lambda - 1)(\phi_3 \alpha - (\phi_2 + C_p \phi_6) \rho + 2(P_M \beta - Q\gamma)(\phi_1 - C_p \phi_7 \rho)) + g \sqrt{4(-\phi_4 \alpha + \eta)^2 + \frac{1}{g^2} \Omega_1^2 \alpha^2 (\lambda - 1)^2 (\phi_3 \alpha + \phi_1 (d - P_M \beta + Q\gamma) - (\phi_2 \alpha + C_p \phi_6 \alpha + C_p \phi_7 (d - P_M \beta + Q\gamma) \rho))^2 + \frac{1}{g^2} 2\Omega_1 \alpha (\lambda - 1) (-3d\phi_4 \alpha (\phi_1 - C_p \phi_7 \rho) + 3\alpha (-P_M \alpha + C_q Q^2 \alpha + \phi_3 \alpha + P_M \phi_3 \beta - Q\phi_1 \gamma) (\phi_1 - C_p \phi_7 \rho) + 4d(\phi_4 \alpha - \eta) (\phi_1 - C_p \phi_7 \rho) - 2(\phi_4 \alpha - \eta) (\phi_3 \alpha - (\phi_2 + C_p \phi_6) \rho + 2(P_M \beta - Q\gamma) (\phi_1 - C_p \phi_7 \rho)))}}{(3\Omega_1 \alpha^2 (\lambda - 1) (\phi_1 - C_p \phi_7 \rho))}} \tag{35}$$

$$P_M^M = \frac{d + s\alpha + Q\gamma - \frac{g(d - (C_q Q^2 + \phi_3) \beta + s(\alpha + \phi_4 \beta) + Q\gamma)}{2g + \Omega_1 \beta (\lambda - 1)(\phi_3 - (\phi_2 + C_p \phi_6) \rho + s(C_p \phi_7 \rho - \phi_1))}}{\beta} \tag{36}$$

$$-g < 0 \tag{39}$$

$$g > (\beta P_R - d\alpha s - \gamma Q) \Omega_1 \tag{40}$$

$$Q^M = \frac{1}{6C_q g \gamma} \left(-2C_q g (d + s\alpha - P_M \beta) + \Omega_1 \gamma^2 (\lambda - 1) (s\phi_1 - \phi_5 + (\phi_2 + C_p (\phi_6 - s\phi_7) \rho)) + g \sqrt{4C_q^2 (d + s\alpha - P_M \beta)^2 + \frac{\Omega_1^2 \gamma^4 (\lambda - 1)^2 (s\phi_1 - \phi_5 + (\phi_2 + C_p (\phi_6 - s\phi_7) \rho))^2}{g^2} + \frac{1}{g} 4C_q \gamma^2 (3g(P_M - \phi_3 + s\phi_4) + 2\Omega_1 (d + s\alpha - P_M \beta) (\lambda - 1) (s\phi_1 - \phi_5 + (\phi_2 + C_p \phi_6 - C_p s\phi_7) \rho))} \right) \tag{37}$$

Also, the profit of each member in the investigated system can be derived by substituting the optimal solutions into Eqs. (10), (11), and (15), respectively.

Proof. See Appendix C.

The collection rate is derived by setting $\frac{\partial \Pi_c}{\partial \tau^R} = 0$ and, solving with respect to τ^R , we find the function given in Proposition 5.

Proposition 5. The optimal reaction of the retailer in retailer-led Stackelberg game is presented in Eq. (41).

$$\tau^R = \frac{\Omega_1 (P_R^R \beta - d - s^R \alpha - Q^R \gamma)}{g} \tag{41}$$

5.3. Retailer-led decentralized scenario

In this scenario, the retailer acts as a leader and plays dominant role in the system, while the other players (retailer and collector) act as followers. This scenario occurs if the retailer has a larger scale than the collector or manufacturer. First, the collector and the manufacturer determine their best reaction. Then, the retailer determines the optimal selling price for the supply chain.

5.3.2. The manufacturer's reaction

By taking into account the collector's reaction, the manufacturer gives his reaction, which can be specified from the first-order condition. Because the profit function of the manufacturer linearly increases with the wholesale price, the best situation reflects $P_R^R = P_M^R$, where P_R^R is the upper bound. As a consequence, the profit will be zero, which is undesirable by the retailer. Because the wholesale price should be in the range of P_R^R and $C_M + C_S$, we take the manufacturer's wholesale price to be $P_M^R = (P_R^R + C_M + C_S)/2$. A similar approach was also used in Maiti and Giri [20].

As for Q^R , we obtained it by substituting Eq. (44) into Eq. (10). Then, by setting $\frac{\partial \Pi_M}{\partial Q^R} = 0$, we get the optimal solution for Q^R ; here, we use a numerical approach.

5.3.3. The retailer's optimal decision

After getting the reactions of the collector and the manufacturer, the retailer determines optimal decisions to maximize his own profit by solving the following equation:

$$\frac{\partial \Pi_M}{\partial s^R} = (d + s^R \alpha - P_R^R \beta + Q^R \gamma) \left(\phi_4 + \frac{\Omega_1(d + s\alpha - P_R \beta + Q\gamma)(\lambda - 1)(\phi_1 - C_P \phi_7 \rho)}{g} + \frac{\Omega_1 \alpha (\lambda - 1)(s\phi_1 - \phi_5 + (\phi_2 + C_P \phi_6 - C_P s \phi_7) \rho)}{g} \right) + \alpha \left(P_M - C_q Q^2 - \phi_3 + s\phi_4 + \frac{\Omega_1(d + s\alpha - P_R \beta + Q\gamma)(\lambda - 1)(s\phi_1 - \phi_5 + (\phi_2 + C_P \phi_6 - C_P s \phi_7) \rho)}{g} \right) - s^R \eta = 0 \tag{42}$$

Corollary 6. When the condition (43) is satisfied, the profit function Π_M is concave in s , Q , and P_M , then we can find the optimal solutions for the optimization problem of the manufacturer.

$$C_q > \max \left\{ -\frac{\gamma^2 \eta}{2\alpha^2(d + s\alpha - P_R \beta + Q\gamma)}, \frac{\sqrt{C_q(C_q(d + s\alpha - P_R \beta)^2 + 3\gamma^2(P_M - \phi_3 + s\phi_4 - (X + sY)\tau)) - C_q(d + s\alpha - P_R \beta)}}{3\gamma} \right\} \tag{43}$$

Proof. See Appendix D.

By solving $P_M^R = \frac{P_R^R + C_M}{2}$ and $\frac{\partial \Pi_M}{\partial s^R} = 0$, the optimal decision of the manufacturer can be obtained.

Proposition 6. The optimal reaction of the manufacturer in retailer-led Stackelberg game is presented in Eq. (44).

$$s^R = -\frac{1}{6\Omega_1 \alpha^2 (\lambda - 1) (\phi_1 - C_P \phi_7 \rho)} (g(2\phi_4 \alpha - \eta) + 4d\Omega_1 \alpha (\lambda - 1) (\phi_1 - C_P \phi_7 \rho) - 2\Omega_1 \alpha (\lambda - 1) (\phi_5 \alpha - (\phi_1 + C_P \phi_6) \alpha \rho + 2(P_R \beta - Q\gamma) (\phi_1 - C_P \phi_7 \rho))) + g \sqrt{\frac{1}{g^2} (g^2 (-2\phi_4 \alpha + \eta)^2 + 4\Omega_1^2 \alpha^2 (\lambda - 1)^2 (-\phi_5 \alpha + (\phi_1 + C_P \phi_6) \alpha \rho + (P_R \beta - Q\gamma) (\phi_1 - C_P \phi_7 \rho) + d(-\phi_1 + C_P \phi_7 \rho))^2 + 4g\Omega_1 \alpha (\lambda - 1) (-3d\phi_4 \alpha (\phi_1 - C_P \phi_7 \rho) - 3\alpha (\frac{1}{2} (C_M + P_R + C_S) \alpha - (C_q Q^2 + \phi_3) \alpha - P_R \phi_4 \beta + Q\phi_4 \gamma) (\phi_1 - C_P \phi_7 \rho) - 2d(-2\phi_4 \alpha + \eta) (\phi_1 - C_P \phi_7 \rho) + (-2\phi_4 \alpha + \eta) (\phi_5 \alpha - (\phi_1 + C_P \phi_6) \alpha \rho + 2(P_R \beta - Q\gamma) (\phi_1 - C_P \phi_7 \rho))))} \tag{44}$$

$$\frac{\partial \Pi_R}{\partial P_R^R} = -\frac{3\beta}{2} - \frac{1}{6\Omega_1\alpha(-1+\lambda)(\phi_1 - C_p\phi_7\rho)} \left(4\Omega_1\phi_1\alpha\beta - 4\Omega_1\phi_1\alpha\beta\lambda - 4C_p\Omega_1\phi_7\alpha\beta\rho + 4C_p\Omega_1\phi_7\alpha\beta\lambda\rho \right. \\ \left. + \frac{(-12\Omega_1\alpha^2(\lambda-1)(\phi_1 - C_p\phi_7\rho)(g(\frac{\alpha}{2} - \phi_4\beta) - 2d\Omega_1\beta(\lambda-1)(\phi_1 - C_p\phi_7\rho) + \Omega_1\beta(P_R\beta - Q\gamma)(\lambda-1)(\phi_1 - C_p\phi_7\rho) + \Omega_1\beta(\lambda-1)(2\phi_5\alpha - 2(\phi_2 + C_p\phi_6)\alpha\rho + (P_R\beta - Q\gamma)(\phi_1 - C_p\phi_7\rho)))}{+8\Omega_1\alpha\beta(\lambda-1)(\phi_1 - C_p\phi_7\rho)(g(-2\phi_4\alpha + \eta) - 4d\Omega_1\alpha(\lambda-1)(\phi_1 - C_p\phi_7\rho) + 2\Omega_1\alpha(\lambda-1)(\phi_5\alpha - (\phi_2 + C_p\phi_6)\alpha\rho + 2(P_R\beta - Q\gamma)(\phi_1 - C_p\phi_7\rho)))} \right) = 0 \\ \left. + \frac{2g \sqrt{\left(\frac{1}{g^2}(-12\Omega_1\alpha^2(\lambda-1)(\phi_1 - C_p\phi_7\rho)(dg\phi_4 + g(\frac{1}{2}(C_M + P_R)\alpha - (C_qQ^2 + \phi_3)\alpha - P_R\phi_4\beta + Q\phi_4\gamma) + d^2\Omega_1(\lambda-1)(\phi_1 - C_p\phi_7\rho) \right. \right.}{+ \Omega_1(P_R\beta - Q\gamma)(\lambda-1)(2\phi_5\alpha - 2(\phi_2 + C_p\phi_6)\alpha\rho + (P_R\beta - Q\gamma)(\phi_1 - C_p\phi_7\rho)) - 2d\Omega_1(\lambda-1)(\phi_5\alpha - (\phi_2 + C_p\phi_6)\alpha\rho} \right. \right.}{\left. \left. + (P_R\beta - Q\gamma)(\phi_1 - C_p\phi_7\rho) \right) + (g(-2\phi_4\alpha + \eta) - 4d\Omega_1\alpha(\lambda-1)(\phi_1 - C_p\phi_7\rho) + 2\Omega_1\alpha(\lambda-1)(\phi_5\alpha - (\phi_2 + C_p\phi_6)\alpha\rho + 2(P_R\beta - Q\gamma)(\phi_1 - C_p\phi_7\rho)))^2 \right)} \right) \quad (45)$$

Corollary 7. If condition $-2\beta < 0$ is satisfied, then the optimal solutions for the retailer problem can be realized.

Proof. See Appendix B.

Also, the profit of each party involved in the investigated system can be obtained by substituting the optimal solutions into Eqs. (10), (11), and (15), respectively.

5.3.4. Collector-led decentralized scenario

In this case, the collector acts as a leader and plays the dominant role in the system, while the other players (retailer and manufacturer) act as followers. This scenario occurs if the collector has a larger scale than the retailer or manufacturer. First, the retailer and the manufacturer determine their best reaction. Then, the collector determines the optimal selling price for the supply chain.

5.3.5. The retailer's reaction

First, we obtain the best reactions to the retailer.

$$\frac{\partial \Pi_R}{\partial P_R^T} = d + s^T\alpha - P_R^T\beta - (P_R^T - P_M^T)\beta + Q^T\gamma = 0 \quad (46)$$

Corollary 8. If condition $2\beta > 0$ is satisfied, then the optimal solutions for the retailer problem can be realized.

Proof. See Appendix B.

Therefore, by solving the first-order condition, there exists a unique optimal reaction. Proposition 7 presents the optimum reaction of the retailer.

Proposition 7. The equilibrium of the retailer decision variable in collector-led Stackelberg game is achieved in Eq. (47).

$$P_R^T = \frac{d + s^T\alpha + P_M^T\beta + Q^T\gamma}{2\beta} \quad (47)$$

5.3.6. The manufacturer's reaction

With the retailer's reaction, the manufacturer gives his reaction, which can be obtained from the first-order condition.

$$\frac{\partial \Pi_M}{\partial s^T} = \left(d + s^T\alpha + Q^T\gamma + \frac{1}{2}(-d - s^T\alpha - P_M^T\beta - Q^T\gamma) \right) (\phi_4 - (\lambda - 1)(\phi_1 - C_p\phi_7\rho)\tau^T) + \frac{1}{2}\alpha(P_M^T - C_qQ^T - \phi_3 + s^T\phi_4 - (\lambda - 1)(s^T\phi_1 - \phi_5 + (\phi_2 + C_p\phi_6 - C_p s^T\phi_7\rho)\tau^T) - s^T\eta) = 0 \quad (48)$$

Corollary 9. When condition (49) is satisfied, the profit function Π_M is concave in s , Q , and P_M , then we find the optimal solutions for the optimization problem of the manufacturer.

$$C_q > \max \left\{ -\frac{\gamma^2\eta}{2\alpha^2(d + s\alpha - P_R\beta + Q\gamma)}, \frac{\sqrt{C_q(C_q(d + s\alpha - P_R\beta)^2 + 3\gamma^2(P_M - \phi_3 + s\phi_4 - (X + sY)\tau))} - C_q(d + s\alpha - P_R\beta)}{3\gamma} \right\} \quad (49)$$

Proof. See Appendix D.

By solving $P_M^R = \frac{P_R^R + C_M}{2}$ and $\frac{\partial \Pi_M}{\partial s^T} = 0$, the optimal decision of the manufacturer is given by Proposition 8.

Proposition 8. The equilibrium values of the manufacturer decision variables in collector-led Stackelberg game are obtained using Eqs. (50) and (51), respectively.

$$s^T = \frac{2\beta(Q^2\alpha C_q - \alpha(d + Q\gamma) + (d + Q\gamma)(\lambda - 1)\tau\phi_1 - (d + Q\gamma)\phi_4 + \alpha(\phi_3 + (\lambda - 1)\tau(\rho\phi_2 - \phi_5 + \rho C_p\phi_6)) - (d + Q\gamma)(\lambda - 1)\rho\tau + C_p\phi_7) + \beta C_M(-\alpha + 2\beta(\phi_4 + (\lambda - 1)\tau(-\phi_1 + \rho C_p\phi_7)))}{\alpha^2 - 4\beta\eta + 4\alpha\beta(\phi_4 - (\lambda - 1)\tau(\phi_1 - \rho C_p\phi_7))} \quad (50)$$

$$P_M^T = \frac{P_R^T + C_M + C_S}{2} \tag{51}$$

As for Q^T , we obtained it by substituting Eqs. (50) and (51) into Eq. (10). Then, by setting $\frac{\partial \Pi_M}{\partial Q^T} = 0$, we get the optimal solution for Q^T ; here, we use a numerical approach.

5.3.7. The collector's optimal decision

By taking into consideration the reactions of both retailer and the manufacturer, the collector determines optimal decisions to maximize his own profit by solving the following equation:

$$\frac{\partial \Pi_C}{\partial \tau^T} \equiv -g\tau - \frac{(\Omega_1\beta(\alpha^2 + 4\phi_4\alpha\beta - 4\beta\eta)(\alpha(d\phi_4 + C_qQ^2\alpha + \phi_3\alpha - C_M(\alpha + \phi_4\beta) + Q\phi_4\gamma) - 2(d - C_M\beta + Q\gamma)\eta))}{(\alpha^2 - 4\beta\eta + 4\alpha\beta(\phi_4 - (\lambda - 1)(\phi_1 - C_p\phi_7\rho)\tau))^2} - \frac{(2\Omega_1\alpha\beta(\lambda - 1)(\phi_5\alpha + \phi_1(d - C_M\beta + Q\gamma) - (\phi_2\alpha + C_p\phi_6\alpha + C_p\phi_7(d - C_M\beta + Q\gamma)\rho)\tau) + (\alpha^2 + 4\phi_4\alpha\beta - 4\beta\eta - 2\alpha\beta(\lambda - 1)(\phi_1 - C_p\phi_7\rho)\tau))}{(\alpha^2 - 4\beta\eta + 4\alpha\beta(\phi_4 - (\lambda - 1)(\phi_1 - C_p\phi_7\rho)\tau))^2} = 0 \tag{52}$$

Corollary 10. When conditions (53) and (54) are satisfied, the profit function Π_c is concave in τ , then we can find the optimal solutions for the optimization problem of the collector.

$$-g < 0 \tag{53}$$

$$g > (\beta P_R - d - \alpha s - \gamma Q)\Omega_1 \tag{54}$$

Proof. See Appendix C.

Also, the profit of each member can be found by substituting the optimal solutions into Eqs. (10), (11), and (15), respectively.

5.4. Decentralized scenario (Nash Game)

In this scenario, the manufacturer, retailer, and collector aim to maximize their own profits by making decisions independently. Because the profit function of the manufacturer linearly increases with the wholesale price, the best situation reflects $P_R^R = P_M^R$, where P_R^R is the upper bound. Consequently, the profit earned by the retailer will be zero, which is undesirable solution for the system. Because the wholesale price should be in the range of P_R^R and $C_M + C_S$, we take the manufacturer's wholesale price to be $P_M^R = (P_R^R + C_M + C_S)/2$.

By taking the first partial derivatives of total profit with respect to s , Q , P_R and τ , respectively, we obtain the following expressions

$$\frac{\partial \Pi_C}{\partial s^N} = (d + s^N\alpha - P_R^N\beta + Q^N\gamma)(\phi_4 - (\lambda - 1)(\phi_1 - C_p\phi_7\rho)\tau^N) + \alpha(P_M - C_qQ^{N2} - \phi_3 + s^N\phi_4 - (\lambda - 1)(s^N\phi_1 - \phi_5 + (\phi_2 + C_p\phi_6 - C_p s^N\phi_7\rho)\tau^N) - s^N\eta) = 0 \tag{55}$$

$$\frac{\partial \Pi_C}{\partial Q^N} = -2C_qQ^N(d + s^N\alpha - P_R^N\beta + Q^N\gamma) + \gamma(P_M - C_qQ^{N2} - \phi_3 + s\phi_4 - (\lambda - 1)(s^N\phi_1 - \phi_5 + (\phi_2 + C_p\phi_6 - C_p s^N\phi_7\rho)\tau^N) = 0 \tag{56}$$

$$\frac{\partial \Pi_R}{\partial P_R^N} = d + s^N\alpha + Q^N\gamma + \beta(P_M - 2P_R^N) = 0 \tag{57}$$

$$\frac{\partial \Pi_C}{\partial \tau^N} = \Omega_1(P_R^N\beta - Q^N\gamma - d - s^N\alpha) - g\tau^N = 0 \tag{58}$$

Corollary 11. By satisfying conditions $2\beta > 0$, (49), (53), and (54), we obtain a unique optimal solution for the vertical Nash model.

Proof. See Appendices B, C, and D.

Then first-order conditions for optimality leads to the following proposition.

Proposition 9. The optimum values of each player decision variables in decentralized Stackelberg game are achieved using Eqs. (59), (60), (61), (62), and (63), respectively.

$$s^N = \frac{(-d\phi_4 - P_M^N\alpha + C_qQ^{N2}\alpha + \phi_3\alpha + P_R^N\phi_4\beta - Q^N\phi_4\gamma - d\phi_1\tau^N + \phi_5\alpha\tau + P_R^N\phi_1\beta\tau^N - Q\phi_1\gamma\tau^N + d\phi_1\lambda\tau^N - \phi_5\alpha\lambda\tau^N - P_R^N\phi_1\beta\lambda\tau^N + Q^N\phi_1\gamma\lambda\tau^N + C_p d\phi_7\rho\tau^N - \phi_2\alpha\rho\tau^N - C_p\phi_6\alpha\rho\tau^N - C_p P_R^N\phi_7\beta\rho\tau^N + C_p Q^N\phi_7\gamma\rho\tau^N - C_p d\phi_7\lambda\rho\tau^N + \phi_2\alpha\lambda\rho\tau^N + C_p\phi_6\alpha\lambda\rho\tau^N + C_p P_R^N\phi_7\beta\lambda\rho\tau^N - C_p Q^N\phi_7\gamma\lambda\rho\tau^N)}{(2\phi_4\alpha - \eta + 2\phi_1\alpha\tau^N - 2\phi_1\alpha\lambda\tau^N - 2C_p\phi_7\alpha\rho\tau^N + 2C_p\phi_7\alpha\lambda\rho\tau^N)} \tag{59}$$

$$Q^N = \frac{1}{3C_q\gamma} \left(\sqrt{(C_q(C_q(d + s^N\alpha - P_R^N\beta)^2 + 3\gamma^2(P_M^N - \phi_3 + s\phi_4 - (\lambda - 1)(s^N\phi_1 - \phi_5 + (\phi_2 + C_p\phi_6 - C_p s^N\phi_7\rho)\tau^N))) - C_q(d + s^N\alpha - P_R^N\beta))} \right) \tag{60}$$

$$P_R^N = \frac{d + s^N\alpha + Q^N\gamma + \beta P_M}{2\beta} \tag{61}$$

$$\tau^N = \frac{\Omega_1(P_R^N\beta - d - s^N\alpha - Q^N\gamma)}{g} \tag{62}$$

$$P_M^N = \frac{(P_R^N + C_M)}{2} \tag{63}$$

The profit earned by the manufacturer, retailer, and collector can be determined by substituting the optimal solutions into Eqs. (10), (11), and (15), respectively.

Table 2
Results of optimal solution.

Optimal decisions	Centralized	Manufacturer-led decentralized	Retailer-led decentralized	Collector-led decentralized	Decentralized (Nash Game)
s	13.22	6.06	6.34	6.9	6.99
P_M	-	739.75	424.60	421.93	513.52
P_R	730.11	988.77	699.20	693.85	877.04
Q	0.79	0.79	0.35	0.32	0.59
τ	0.74	0.21	0.46	0.47	0.31
Π_M	-	16784.40	14532.30	14492.20	14242.60
Π_R	-	6201.19	14713.70	14788.60	13214.60
Π_T	-	137.06	634.55	653.72	292.07
Π	30719.50	23122.70	29880.50	29934.50	27749.30

Table 3
Numerical calculation of the technical condition in each corollary.

Corollaries	Remarks
Corollary 1	LHS = 0.1, RHS = 4.983, satisfies LHS < RHS in Eq. (17)
Corollary 2	LHS = -32.674, RHS = -98.807,3, satisfies LHS > RHS in Eq. (18)
Corollary 3	LHS = -0.2, RHS = 0, satisfies LHS < RHS as the condition for Corollary 2 LHS = -6000, RHS = 0, satisfies LHS < RHS in Eq. (28)
Corollary 4	LHS = 6000, RHS = 154.402, satisfies LHS > RHS in Eq. (29)
Corollary 5	LHS = 6, RHS = max{-1.811; 5.012}, satisfies LHS > RHS in Eq. (34) LHS = -6000, RHS = 0, satisfies LHS < RHS in Eq. (39)
Corollary 6	LHS = 6000, RHS = 332.212, satisfies LHS > RHS in Eq. (40)
Corollary 7	LHS = 6, RHS = max{-0.842; -0.642}, satisfies LHS > RHS in Eq. (43)
Corollary 8	LHS = -0.2, RHS = 0, satisfies LHS < RHS as the condition for Corollary 7 LHS = 0.2, RHS = 0, satisfies LHS > RHS as the condition for Corollary 8
Corollary 9	LHS = 6, RHS = max{-0.829; -0.699}, satisfies LHS > RHS in Eq. (49)
Corollary 10	LHS = -6000, RHS = 0, satisfies LHS < RHS in Eq. (53) LHS = 6000, RHS = 337.088, satisfies LHS > RHS in Eq. (54)
Corollary 11	LHS = 0.2, RHS = 0, satisfies LHS > RHS as the condition for Corollary 11 LHS = 6, RHS = max{-1.241; 1.324}, satisfies LHS > RHS in Eq. (49) LHS = -6000, RHS = 0, satisfies LHS < RHS in Eq. (53) LHS (g) = 6000, RHS = 225.379, satisfies LHS > RHS in Eq. (54)

LHS = Left hand side in the equation.
RHS = Right hand side in the equation.

6. Numerical analysis

This section presents the performance of the proposed models described in the previous section. The model would generally suit different types of industry, but we mainly refer to the typical lead acid battery industry. A lead acid battery consists of two main components, which are the pure lead that acts as the negative electrode and a lead dioxide that acts as the positive electrode. The other components of the battery are metallic grids, metallic connections, electrolyte and polypropylene casing. Lead acid batteries have been widely used in automotive applications, for example for lighting, starting and supplying power for various kinds of vehicles. In 2007, about 1200 million batteries were sold worldwide and their sales are believed to continue to rise along with the growth in the number of vehicles worldwide [62]. In 2015, the battery industry had an annual market of \$33 billion, which means it is one of the very valuable industries in the world [63].

New lead acid batteries are commonly produced from both manufacturing and remanufacturing processes. Remanufactured batteries will have the same quality as manufactured batteries and will be sold to the primary market. The refurbished batteries which have lower quality than remanufactured batteries are sold to the secondary market at a lower price. Lead acid batteries are manufactured through processes such as casting, pasting, curing, assembling, drying and stamping. Some of these processes are harmful because they generate carbon emissions. For example, grid casting is the process of melting lead or ingot materials, then pouring the liquid lead into a mold to form a grid. In the process of forming a grid, the mold is coated with cork spray. Cork spray coats the mold as heat insulation so that the liquid freezes

simultaneously in all parts of the mold. During the casting process, carbon emissions are released continuously to the environment through an exhaust pipe.

Although the lead acid battery industry is very productive and profitable, it produces a lot of carbon emissions. Thus, serious efforts are needed to lessen the carbon emissions coming from the manufacturing process. Adopting green technology would be the best strategy for the manufacturer to minimize these emissions. Many industries employ new green technologies in their production processes and materials (wet scrubbers, electrostatic precipitators, fabric filters) to reduce the emissions [55]. In addition, the regulator often implements a strict policy on carbon emitters to limit the emissions resulting from the manufacturing process. In practice, a carbon cap-and-trade policy is commonly applied by the regulator to restrict the emissions released from industries.

The parameters values used to perform numerical analysis are mainly adapted from the works of Maiti and Giri [20] and Bai et al. [15]. The parameters used are: $C_m=60$, $C_s=70$, $C_{insp}=15$, $C_q=6$, $C_{rem}=30$, $C_{ref}=20$, $C_{rw}=50$, $C_{im}=10$, $C_t=15$, $C_{it}=5$, $C_{wd}=8$, $P_{2nd}=500$, $P_m=800$, and $P_T=30$. The basic demand $d=120$ with $\alpha=0.5$, $\beta=0.1$, and $\gamma=0.95$. We use $e_1=40$, $e_2=37$, $e_3=23$, $e_4=10$ and $b_1=0.42$, $b_2=0.35$, $b_3=0.28$, $b_4=0.25$, and also use $C_p=2.5$, $C=2,000$, and $\eta=25$. The rest of the variables are $Q_r=0.2$, $Q_f=0.1$, $Q_s=0.5Q$, $f=0.04$, $\rho=0.7$, $\lambda=0.10$. The results obtained for the optimal solution are presented in Table 2. Table 3 presents a numerical calculation that shows that the technical condition in each corollary is satisfied.

The optimal green technology levels in the five models are satisfied in the following order: $s^C > s^N > s^T > s^R > s^M$. The wholesale price is

Table 4
Amount of emissions generated from each stage and the number of units processed at each stage.

Investigation on	Stage	Coordination policy				
		Centralized	Manufacturer-led	Retailer-led	Collector-led	Decentralized-led
Unit processed at	Manufacturing	29.35	21.60	38.39	38.62	29.25
	Remanufacturing	25.00	3.29	15.19	15.76	7.10
	Refurbishing	1.17	0.86	1.54	1.54	1.17
	Reworking	10.71	1.41	6.51	6.75	3.04
Demand		54.35	24.90	53.58	54.38	36.35
Emissions generated from	Manufacturing	999.42	809.40	1420.84	1419.95	1084.20
	Remanufacturing	820.28	114.92	540.09	556.79	245.31
	Refurbishing	22.40	18.41	32.31	32.25	24.62
	Reworking	72.70	11.98	56.00	57.09	25.11
	Total emissions	1914.80	954.73	2049.24	2066.09	1379.25

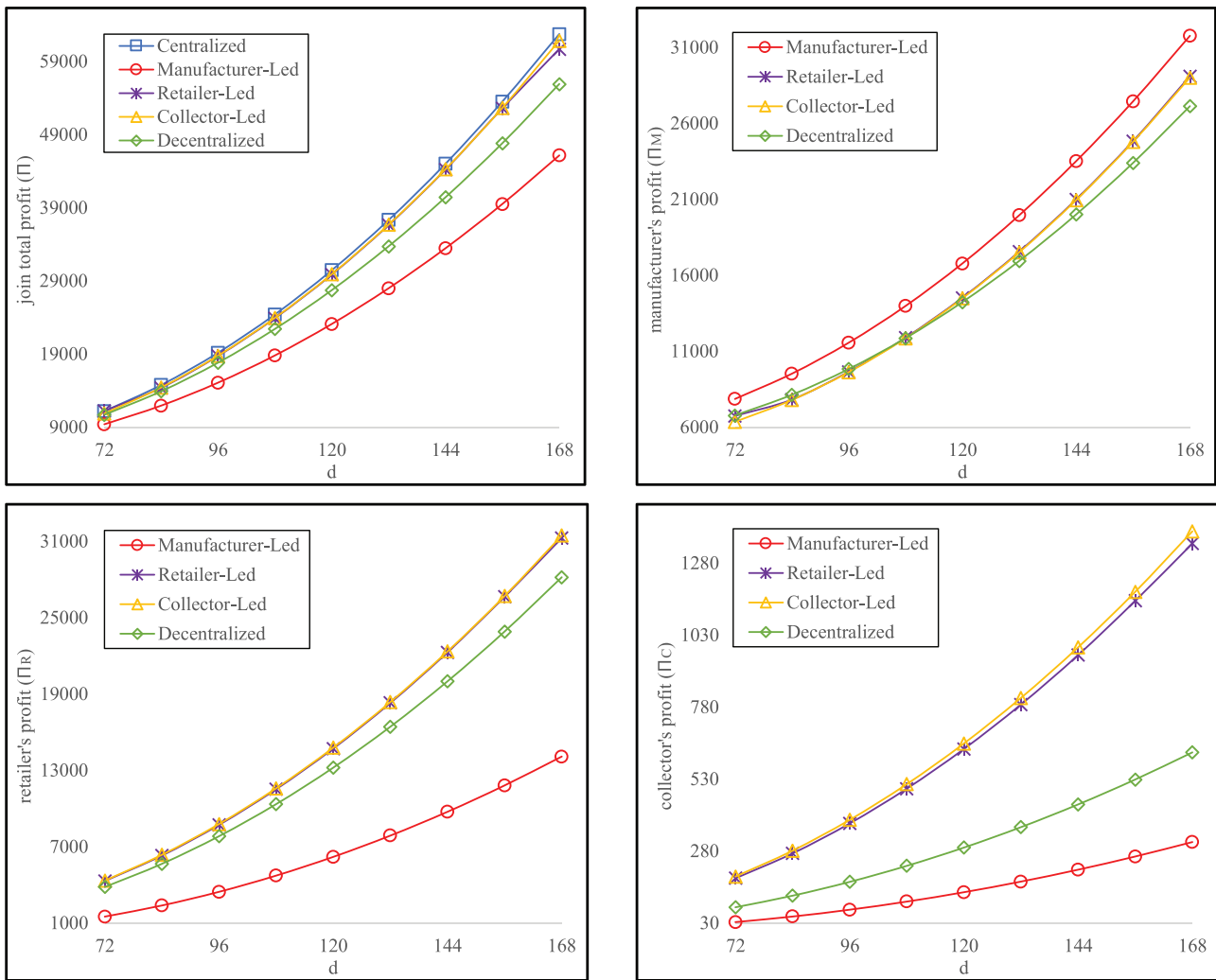


Fig. 2. Effects of d on each player's profit.

$P_M^M > P_M^N > P_M^R > P_M^T$. The retailer's selling price sequence is $P_R^M > P_R^N > P_R^C > P_R^R > P_R^T$. The sequence of product quality satisfies the following relationship: $Q^C = Q^M > Q^N > Q^R > Q^T$. The relationship of the collection rate is given by $\tau^C > \tau^T > \tau^R > \tau^N > \tau^M$. Also, the profit sequence for all players and the whole system in the five models satisfies the following relationship: $\Pi_M^M > \Pi_M^R > \Pi_M^T > \Pi_M^N$, $\Pi_R^T > \Pi_R^R > \Pi_R^N > \Pi_R^M$, $\Pi_T^T > \Pi_T^R > \Pi_T^N > \Pi_T^M$, $\Pi^C > \Pi^T > \Pi^R > \Pi^N > \Pi^M$. The results show that the total profit of the centralized scenario is significantly higher than that in other scenarios. Compared with the profit obtained by the decentralized scenario, in which each party decides independently, the cooperation among parties involved in the supply chain can lead to an increase at most of 32.85% in profit. The profit per actor can be obtained in two ways, but these require decisions or assumptions. The first is to decide the split of total profit for each actor and then calculate the transfer prices. Second, the transfer prices are decided and then the profit obtained by each actor is calculated. However, analysis of the transfer price and profit allocation is beyond the scope of this paper.

The technology level achieved by the centralized scenario is also higher than the other scenarios. The results also indicate that the centralized and manufacturer-led scenarios have a better quality product than others. Furthermore, the lowest selling price is obtained from the collector-led scenario, while the selling price of the centralized scenario is quite moderate. The collection rate of the centralized scenario is also higher than the others. Having many returned items, the system has an opportunity to reduce the total cost, since the remanufacturing cost is

always lower than the manufacturing cost. The results from Table 1 also suggest that the retailer-led decentralized scenario is the best scenario that gives solution for all players. In this scenario, the percentages of profit gained by the manufacturer and retailer are 48.41% and 49.4%, respectively, which is almost equally split among the two parties.

Table 4 shows the number of units processed in each process and the amount of emissions generated by the manufacturer. The highest demand occurs when centralized policy or collector-led policy is applied to coordinate the parties in the CLSC. Conversely, the lowest demand will occur if the system adopts a manufacturer-led policy. We observe that the manufacturing will process more items if a collector-led policy is applied. In addition, if a centralized policy is selected by the system, the remanufacturing and reworking processes generate more items than if other scenarios are adopted. It is also observed that the investigated CLSC under a centralized policy results in more defective items than the other policies. The number of units processed by refurbishing tends to be lower than that of other processes and is lowest if a manufacturer-led policy is utilized. Furthermore, the results from the table also show that the collector-led scenario releases the highest carbon emissions, while the lowest carbon emitter is the manufacturer-led scenario. This is understandable since the demand in the collector-led scenario is higher than the demand in the manufacturer-led scenario. In addition, the production processes in the centralized scenario seem to be greener than other scenarios, thus resulting in a lower carbon emission for each unit item produced by the system. We observe that the per unit carbon emission generated from the manufacturing process is 35.23 in the

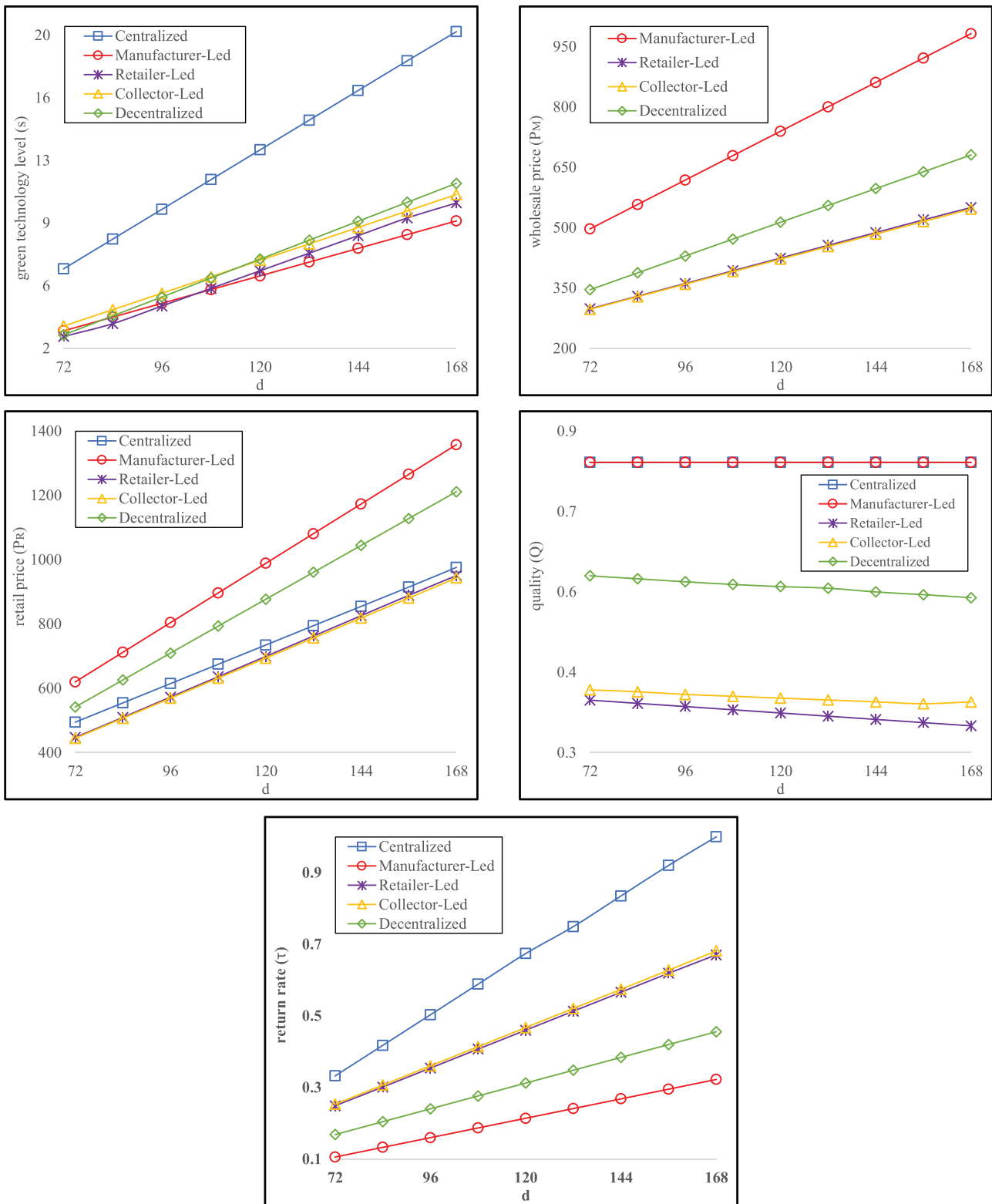


Fig. 3. Effects of d on decision variables.

centralized scenario, which is slightly lower than other scenarios (37.94–38.33).

7. Sensitivity analysis

In this section, we perform a sensitivity analysis of some useful parameters in order to study their effects on the decision variables as

well as the profits earned by the members involved in the proposed system. The results of sensitivity analysis are described as follows:

- (i) Figs. 2 and 3 present the optimal solutions and profit for different values of demand. It can be seen that when the basic market demand (d) increases, all of the players' profits, as well as the whole system, increased significantly. Also s , P_M , P_R , and τ increase while

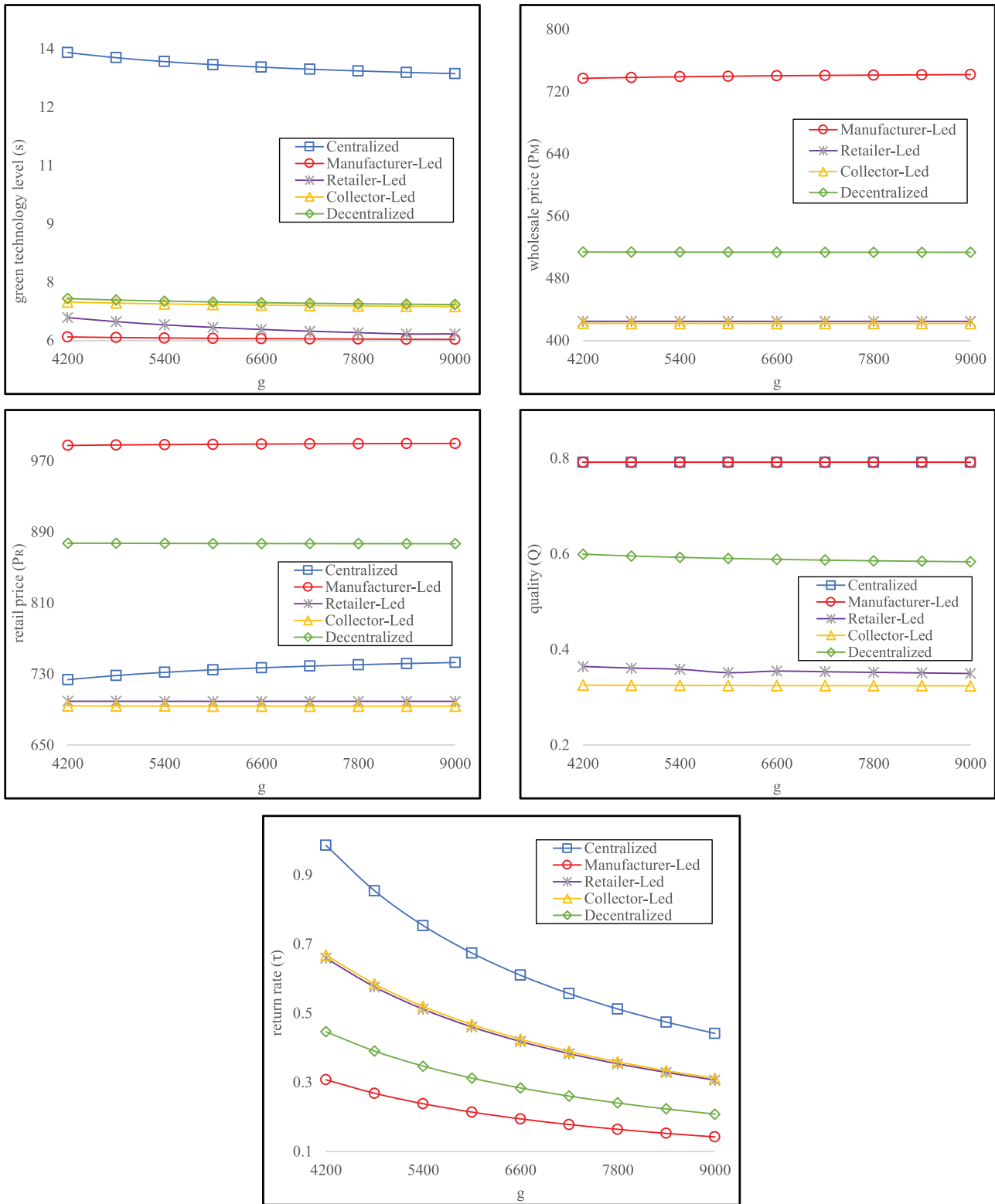


Fig. 4. Effects of g on decision variables.

Q decreases. For example, when d increases from 120 to 168, the green technology level, wholesale price, retailer price, and collection rate increase on average by 54.95%, 31.13%, 36.04%, and 47.34% respectively, while the quality level decreases on average by 2.62%. In the centralized and manufacturer-led Stackelberg, the quality level remains almost unchanged. When the demand increases, the number of products produced by the system and

product sales will increase. This will also increase the revenue obtained by each party in the system. In Fig. 3, it can also be observed that the value of the s in the centralized scenario is much higher than the value in all the decentralized models. In addition, the increase that occurred was also more significant. When the value of d increases from 120 to 168, the value of s in the centralized model also increases from 13,095 to 19,701, whereas in

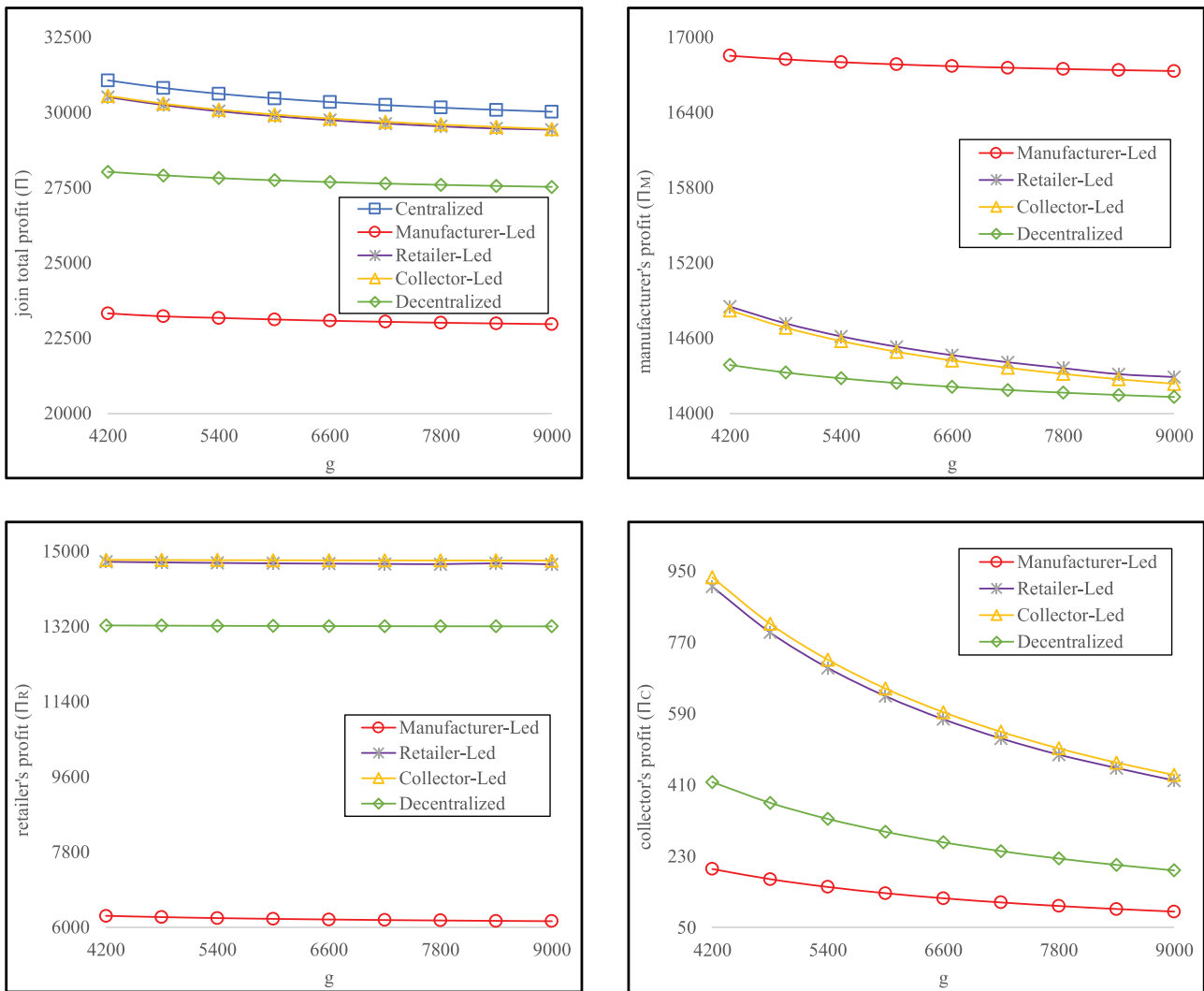


Fig. 5. Effects of g on decision variables.

the other decentralized models an increase occurred in the range of 6055 to 11,226. This indicates that, in the centralized model, it is optimal that manufacturers maximize their green technology levels to reduce the cost of the carbon emissions incurred so that their profits will increase. This is because the profit of the manufacturer is the most dominant among all the parties involved, as it is known that in the centralized model the preferred option is the maximization of the joint total profit. This applies to all parameter changes, especially to the value of s .

(ii) When the collection effort investment (g) increases, all the decision variables, such as s , P_M , P_R , and Q , remain almost unchanged except τ . This finding is compatible with the real system, when the third party or collectors invest a large effort to collect used products, which will only affect the value of the collection rate. The higher the investment costs that must be incurred, the more the collectors will reduce the collection rate to prevent losses in profit. As a result, the profits of collectors and manufacturers (due to the low value of the collection rate) will decrease, which will lead to the decreasing of the joint total profit. The effects of g on the optimal solutions and profit are shown in Fig. 4 and Fig. 5, respectively. As shown in Fig. 4, it is observed that, as concerns the return rate, the centralized model offers a higher return rate to the manufacturer than the other channel power structures. Meanwhile, the manufacturer-led Stackelberg model offers a lower return rate than the other structures.

(iii) As α increases, the green technology level (s) increases drastically. Consequently, the profit of all players as well as of the whole system increases. The effects of α on the optimal solutions and the profit are shown in Figs. 6 and 7. In the real system, when the green technology level has a large impact on the demand rate, the manufacturer will increase the green technology level to gain more customers. In an effort to increase it, the manufacturer must make higher investments, which will increase the wholesale price. Consequently, the higher wholesale price provided by the manufacturer will make the retailer set the selling price at a higher level to maintain his profit. The increase of α gives a significant reduction in total emissions. In a decentralized scenario, increasing α from 0.3 to 0.7 can lead to a reduction of 8.28% in total emissions. We observe that the sharpest emission reduction (11.02%) occurs in the centralized scenario.

(iv) We observe that the changes of β significantly influence the selling price, wholesale price, technology level and product quality. The higher β , the lower the selling price, so the demand decreases and the profit significantly decreases. The manufacturer will also follow the retailer's decision and reduce the wholesale price to maintain his profit. In order to reduce the wholesale price, the manufacturer must suppress all the decision variables, such as the green technology level and product quality. The collectors also reduce the collection rate (τ). This causes a decrease of the profits of all parties involved and also the profit of the whole system. This

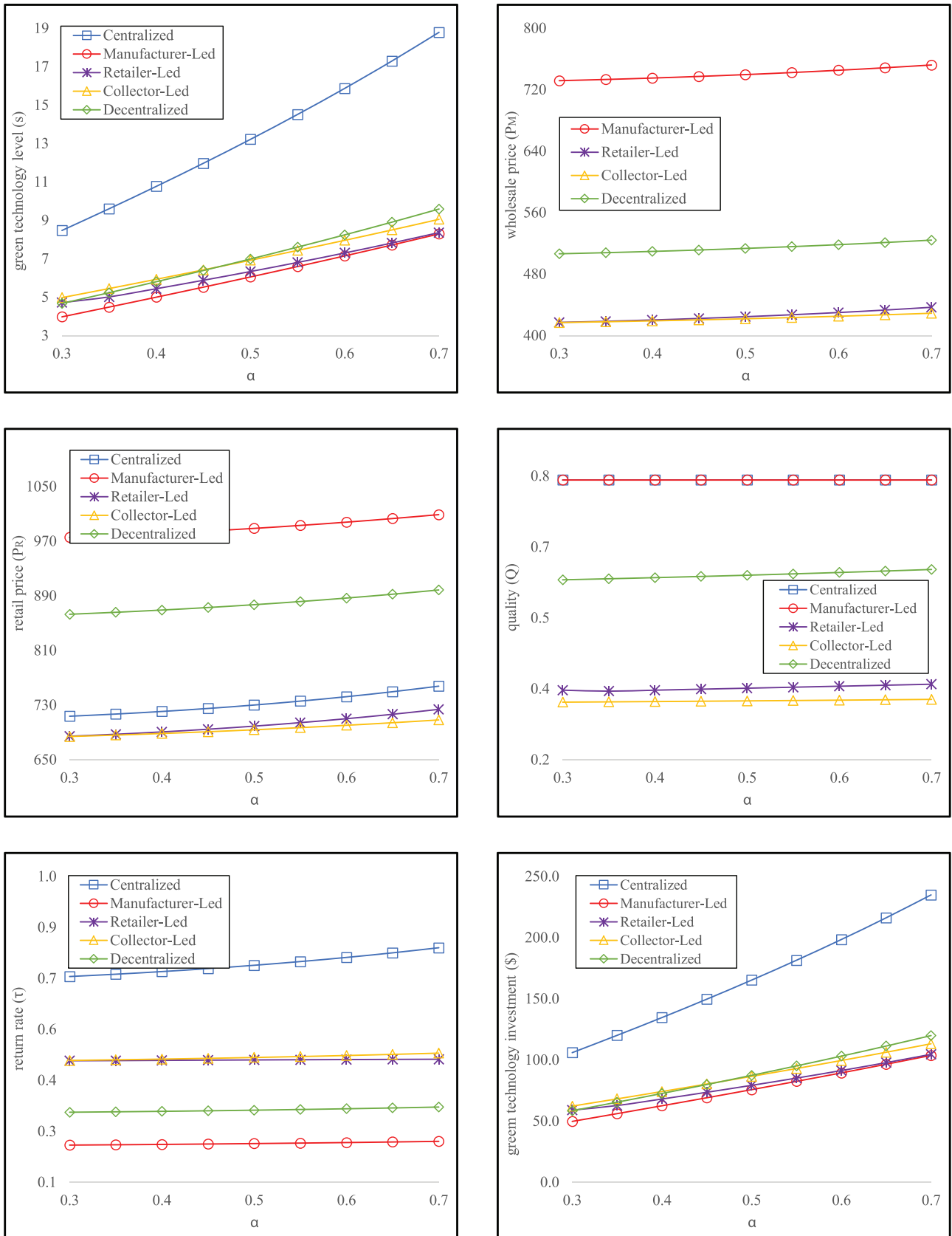


Fig. 6. Effects of α on decision variables.

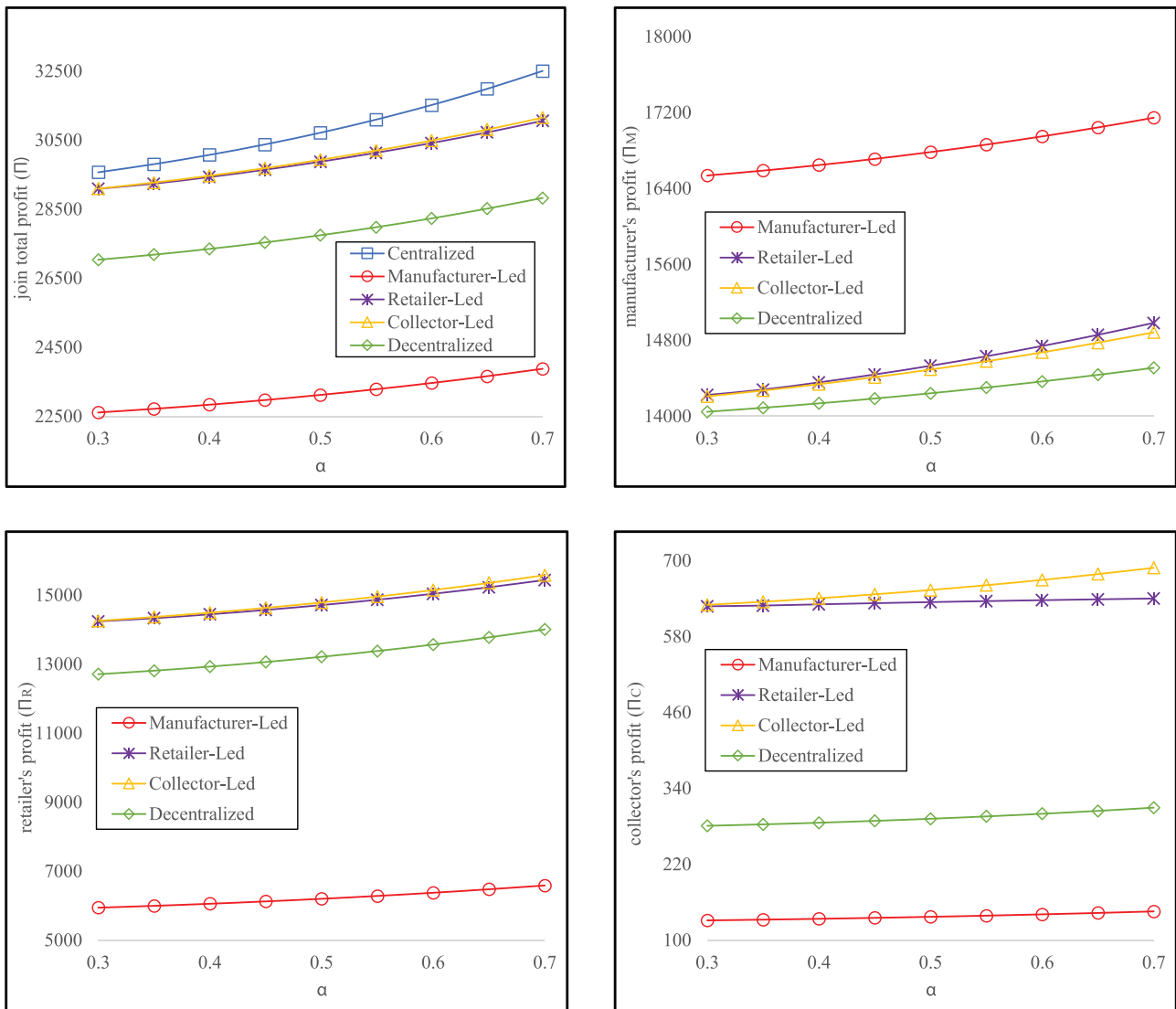


Fig. 7. Effects of α on each player's profit.

is quite true in reality, as when the retail price has a significant effect on the demand rate, the retailer will reduce his selling price in order to gain more customers. The effects of the changes of β on the model's behavior seem to be the total opposite of the changes of α . The effects of β on the optimal solutions and the profit are shown in Figs. 8 and 9, respectively. In the case of retailer prices, the manufacturer-led Stackelberg scenario offers a higher price than other power structure channels, while the retailer-led Stackelberg model offers a lower price than the other power structure channels. As an example in Fig. 8, when the value of β is equal to 0.12, the optimal selling price value for the manufacturer-led Stackelberg and retailer-led Stackelberg are \$829.942 and \$588.04, respectively. This means that the retailer-led Stackelberg model is more beneficial for the customer than the other structured channels. This is because in a manufacturer-led Stackelberg, retailers will adjust the wholesale price set by the manufacturers which were previously already high. Meanwhile, in the retailer-led Stackelberg scenario, the retailer will set a lower price in order to induce the customer to buy more products, thus increasing the sales revenue.

(v) The impact of γ on the proposed model is shown in Fig. 10 and Fig. 12. From the figure, we can see that the increase of γ has a significant effect on the product quality. In the real system, when the product quality has a large impact on the demand, the

manufacturer will increase it in order to attract more customers. In an effort to upgrade the product quality, the manufacturer must spend more on the effort to improve the quality (quality cost), and in order to reduce these costs the manufacturer will increase the collection rate (τ). This is due to the cost of improving the quality of used products through the remanufacturing process, which is cheaper than making improvements to the quality of raw materials with a regular production process. The relation between γ and the quality cost is shown in Fig. 11. In the matter of product quality, we observe that the centralized and manufacturer-led Stackelberg scenario are more acceptable choices than the other scenarios for the customer. These scenarios offer a higher quality level than the other channel power structures, while the collector-led Stackelberg scenario results a lower quality level than the other scenarios.

(vi) When we investigate the impact of the carbon cap (C) on the proposed model, we observe that it does not give significant effect on the optimal solution of the manufacturer, retailer, and collector. A large carbon cap value will benefit the main party that produces carbon emissions. The profits are obtained from the sale of the remaining emissions owned by the manufacturer. The effects of C on the revenue (cost) from buying or selling the extra carbon permits are shown in Fig. 13. From the figure, we can see that when the carbon cap (permit) is 2000, the manufacturer needs to

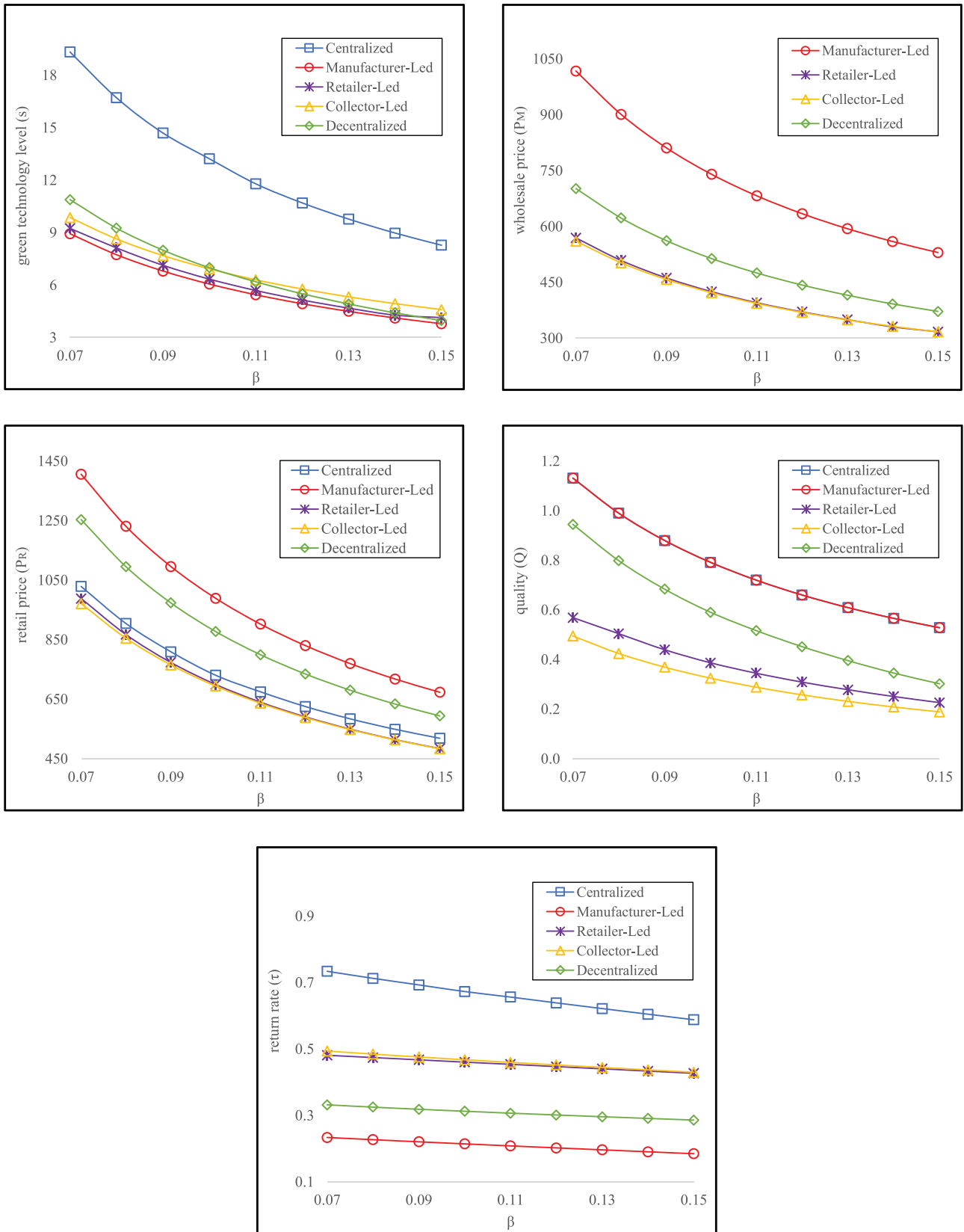


Fig. 8. Effects of α on decision variables.

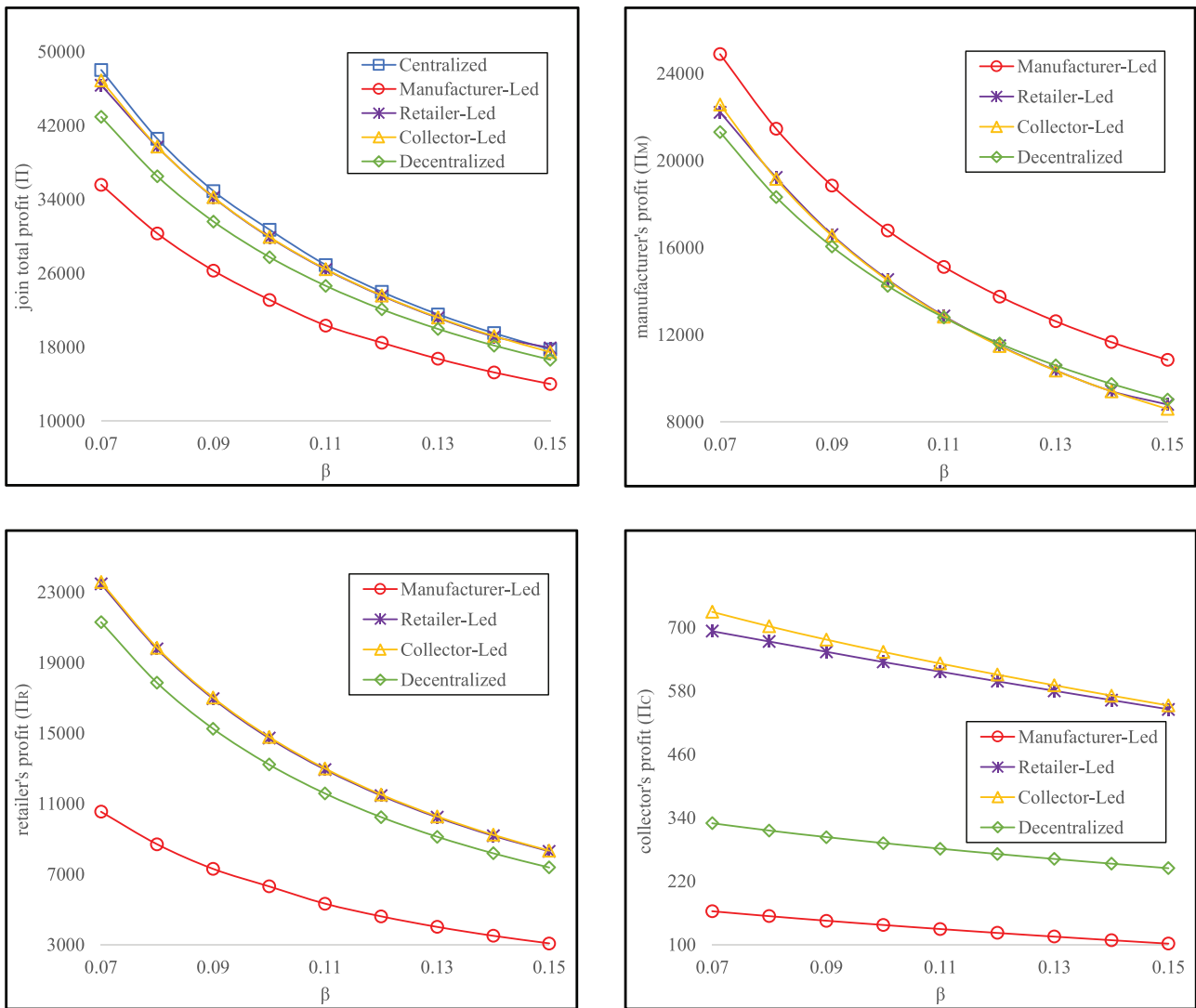


Fig. 9. Effects of α on each player's profit.

pay around \$5000–\$6000 in order to buy the carbon allowance from another firm. However, when the upper limit of the allocated carbon is loosened to 5000, the manufacturer will get a revenue of around \$2000 due to selling the extra carbon permits (the negative signs indicate the revenue).

8. Managerial insights

This paper provides a few important insights on managing a complex closed-loop supply chain, where different types of actions may be taken in various stages of the system. We explored various factors such as coordination policy, green technology investment, the three recovery processes, carbon emissions and an imperfect production system, which are commonly found in the real situation. The model can assist managers to choose the most suitable coordination policy to adopt for the CLSC to maximize the total profit. As shown in our study, the centralized scenario performs better in generating the supply chain's total profit than the other scenarios. However, it is always complicated to take a central action in a system that consists of multiple parties, as each will have a different interest. A wise supply chain leadership would be needed to ensure that all parties involved in this scenario act in such a way as to support the maximum benefit of the whole system. This may involve redesigning the incentive and compensation system across parties within the closed-loop supply chain system.

The proposed model also gives guidance for managers to make an effective plan for their production system. Production plans in each process (manufacturing, remanufacturing and refurbishing) and the required materials can be determined by taking into account the carbon emissions resulting from each process. In addition, to make sure that the production process runs well, the manufacturer must have good coordination with the collector so that the needs of used products can always be satisfied. Managers need to pay more attention to controlling the quality of the used products supplied by the collector. When the quality level of the used product is too low, it may not be possible to re-use and this will mean the company loses the opportunity to gain more profit.

Our research proves that investment in green technology significantly affects the emission reduction and the demand. By adopting a cleaner technology, the manufacturer can control the emissions released from the manufacturing, remanufacturing, refurbishing and reworking processes to comply with carbon cap-and-trade regulations. Thus, the selection of the most suitable type of green technology will be a challenge for managers. To choose the right technology, managers need to pay attention to several important aspects, such as funding requirements, emission levels and the compatibility of the technology with the other machines used on the production floor.

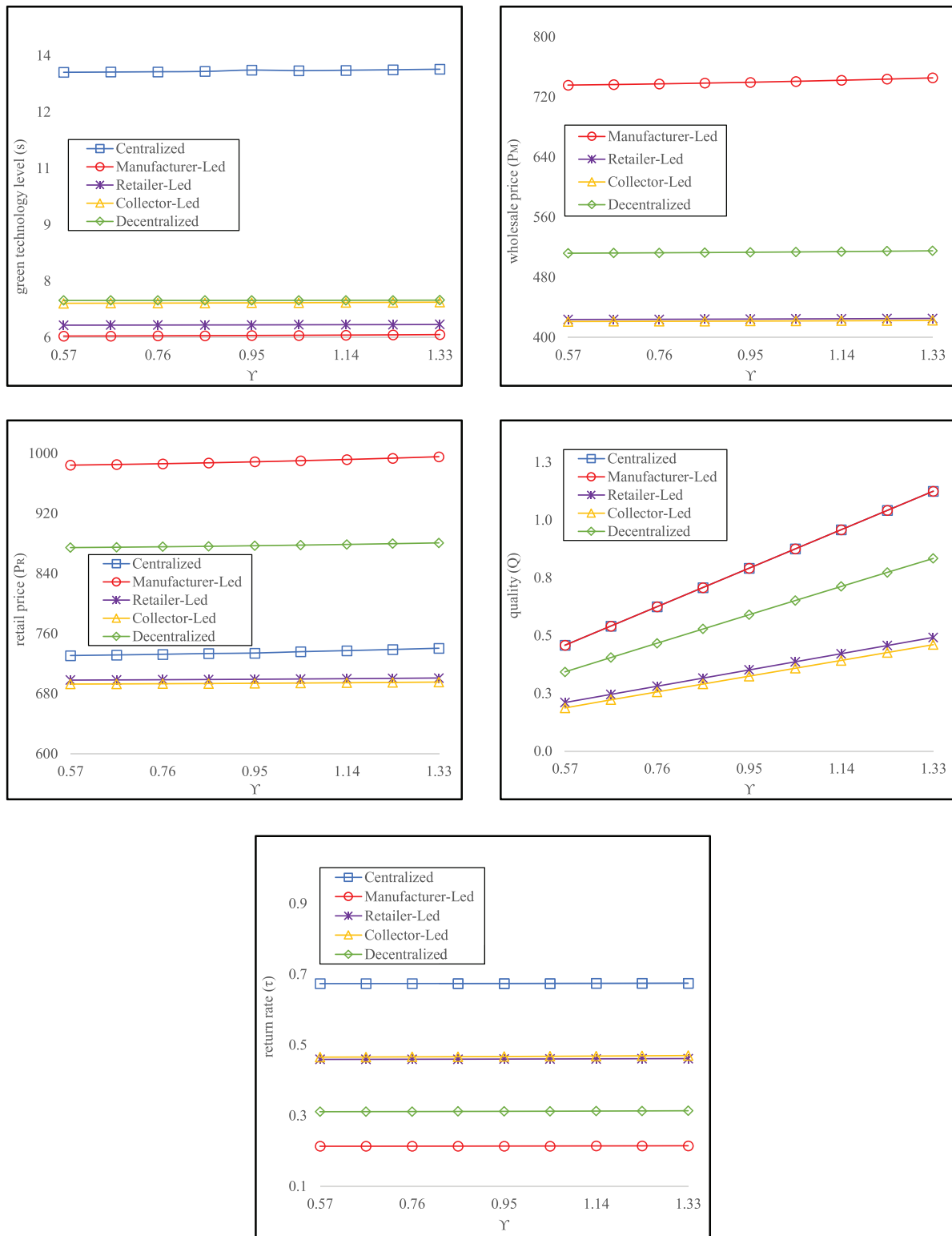


Fig. 10. Effects of γ on the decision variable.

9. Conclusions

In this paper, a mathematical model for a closed-loop supply chain model was developed by considering the reworking processes, waste disposal activity, and carbon emission costs, where the level of demand depends on the quality of the product and the selling price. Furthermore, we constructed the model under five different scenarios, which are centralized, decentralized, and three different channel

leaderships (manufacturer, retailer, collector) with Stackelberg game theory. Two recovery processes, remanufacturing and refurbishing, were applied in the proposed model, where the remanufactured and newly manufactured products have the same quality. Meanwhile, the refurbished products have lower quality than new products, thus they must be sold to secondary markets at a cheaper price. The carbon cap-and-trade regulation is introduced as an instrument to restrict carbon emissions.

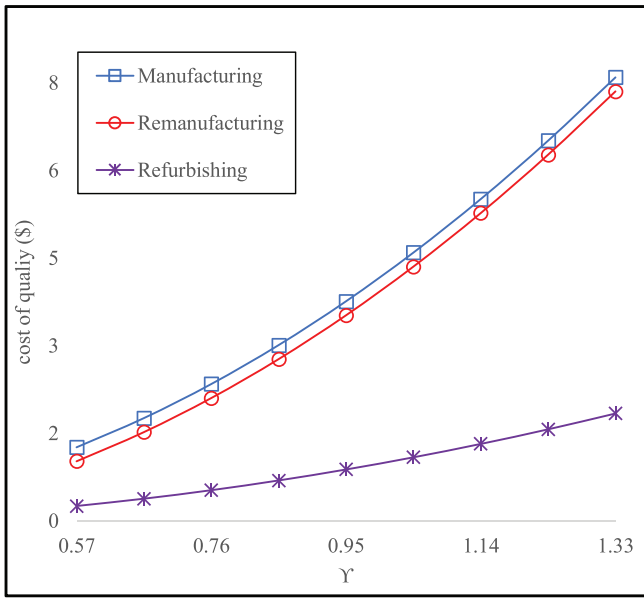


Fig. 11. Effects of γ on quality costs.

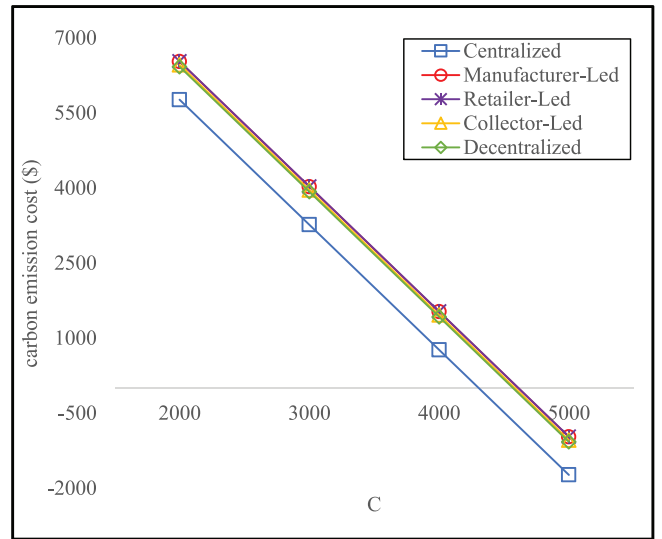


Fig. 13. Effects of C on carbon emission cost.

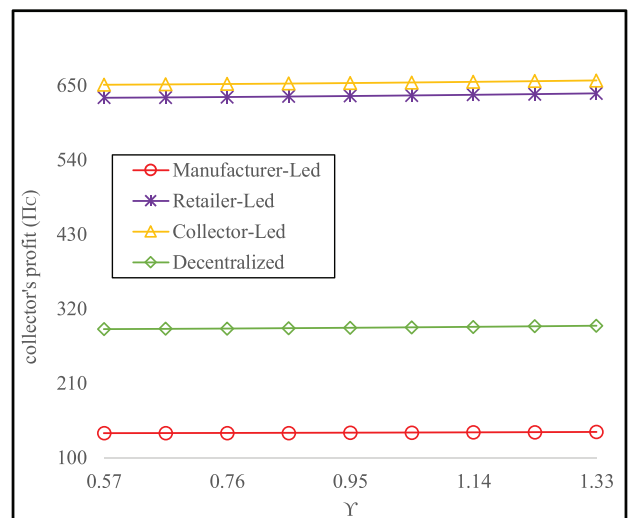
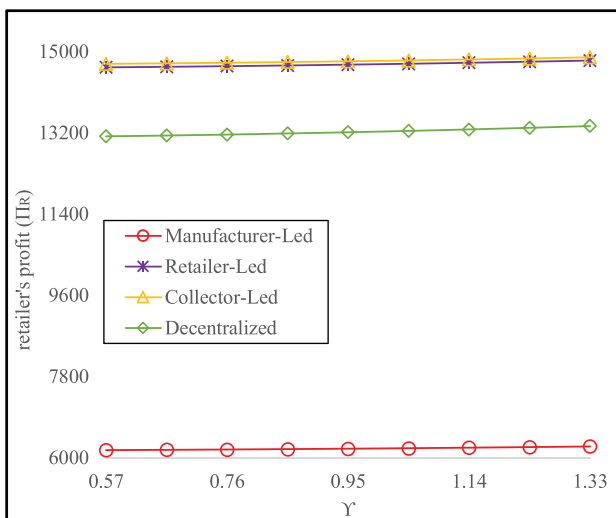
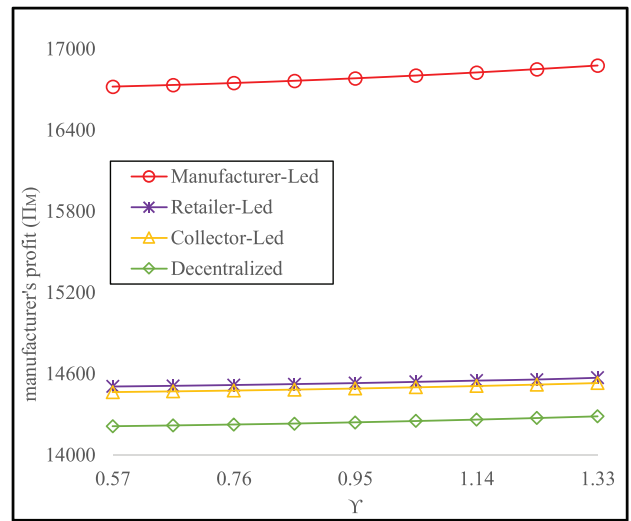
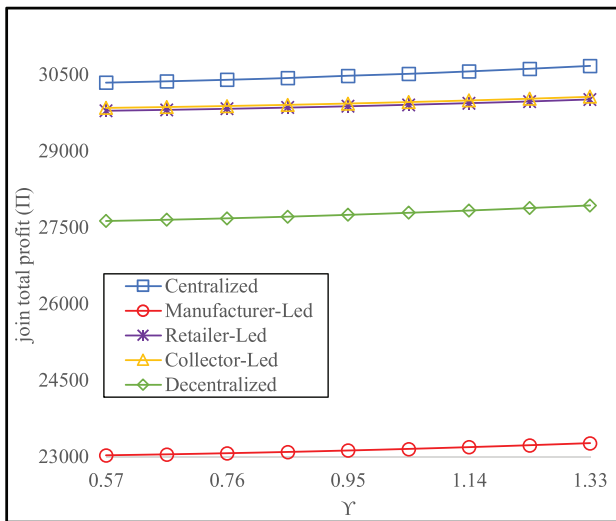


Fig. 12. Effects of γ on each player's profit.

The main findings obtained in this paper are presented as follows. (1) Based on the analytical comparison, we observe that the centralized scenario performs better in maximizing the total profit compared to the other scenarios. The product quality, technology level and collection rate in the centralized scenario are all better than in other scenarios. Since the emissions per unit product can be significantly reduced, the centralized scenario tends to be greener than the others. (2) The profit under the retailer-led Stackelberg is more acceptable than the other four different scenarios. In this scenario, the profit obtained in the CLSC can be shared among players in an equitable manner. This is because when a retailer becomes a leader, he tends to reduce the selling price to increase market demand. This increase in demand certainly has a positive impact on the other players' profits. Moreover, the manufacturer will obtain the maximum benefit when a manufacturer-led scenario is applied. In this scenario, the wholesale price and product quality are at the highest level, thus generating the highest profit for the manufacturer. (3) When the demand is dependent on the selling price, technology level and product quality level, the changes of sensitivity factors will significantly influence the decision variables and profit. The higher α , the higher the technology level, selling price and wholesale price, thus increasing the total profit. The higher β , the lower the selling price, technology level and product quality, thus reducing the total profit. The higher γ , the higher the product quality, yet the total profit increases. (4) When the manufacturer is the primary emitter of carbon emissions in the CLSC, reducing the carbon cap will result in a

reduction of the manufacturer's profit. In addition, the decentralized scenario seems to be more sensitive to carbon cap changes than the other scenarios. (5) By allowing the manufacturer to invest in both green technology and product quality, the carbon emissions generated from the manufacturing system are reduced and the performance of the product is increased. As a consequence, the demand is increased as a sign of the increase of the product's acceptability level in the market.

For future research, the model can be extended by taking into account some features of closed-loop systems, such as stochastic demand and stochastic returns. Also, this model could be developed by considering multiple products rather than the single product in this paper. Another interesting development of this work will be to include logistical issues, such as transportation, inventory, setup and ordering. Finally, the model can also be extended by assuming that the amount of carbon emissions released from the manufacturing and re-manufacturing processes is influenced by the production rate.

CRedit authorship contribution statement

Wakhid Ahmad Jauhari: Conceptualization, Methodology, Writing - original draft. **Niimas Ayu Frensilia Putri Adam:** Data curation, Software, Visualization. **Cucuk Nur Rosyidi:** Validation, Formal analysis. **I Nyoman Pujawan:** Writing - review & editing, Supervision. **Nita H. Shah:** Writing - review & editing, Supervision.

Appendix A

Proof of Proposition 1

The Hessian matrix for $\Pi^C(s, Q, P_R, \tau)$ is given as follows:

$$H = \begin{pmatrix} \frac{\partial^2 \Pi^C}{\partial s^2} & \frac{\partial^2 \Pi^C}{\partial s \partial Q} & \frac{\partial^2 \Pi^C}{\partial s \partial P_R} & \frac{\partial^2 \Pi^C}{\partial s \partial \tau} \\ \frac{\partial^2 \Pi^C}{\partial Q \partial s} & \frac{\partial^2 \Pi^C}{\partial Q^2} & \frac{\partial^2 \Pi^C}{\partial Q \partial P_R} & \frac{\partial^2 \Pi^C}{\partial Q \partial \tau} \\ \frac{\partial^2 \Pi^C}{\partial P_R \partial s} & \frac{\partial^2 \Pi^C}{\partial P_R \partial Q} & \frac{\partial^2 \Pi^C}{\partial P_R^2} & \frac{\partial^2 \Pi^C}{\partial P_R \partial \tau} \\ \frac{\partial^2 \Pi^C}{\partial \tau \partial s} & \frac{\partial^2 \Pi^C}{\partial \tau \partial Q} & \frac{\partial^2 \Pi^C}{\partial \tau \partial P_R} & \frac{\partial^2 \Pi^C}{\partial \tau^2} \end{pmatrix}$$

$$= \begin{pmatrix} -\eta + 2\alpha(\phi_4 - Y\tau) & -2C_q Q\alpha + \gamma(\phi_4 - Y\tau) & \alpha - \beta(\phi_4 - Y\tau) & -\Omega_1\alpha + (X - Ys)\alpha - Y(d + \alpha s - \beta P_R + \gamma Q) \\ -2C_q Q\alpha + \gamma(\phi_4 - Y\tau) & -4C_q Q\gamma - 2C_q(d + \alpha s - \beta P_R + \gamma Q) & 2C_q Q\beta + \gamma & -\Omega_1\gamma + (X - Ys)\gamma \\ \alpha - \beta(\phi_4 - Y\tau) & 2C_q Q\gamma + \gamma & -2\beta & \Omega_1\beta - (X - Ys)\beta \\ -\Omega_1\alpha + (X - Ys)\alpha - Y(d + \alpha s - \beta P_R + \gamma Q) & -\Omega_1\gamma + (X - Ys)\gamma & \Omega_1\beta - (X - Ys)\beta & -g \end{pmatrix}$$

where

$$\phi_1 = b_4 C_p$$

$$\phi_2 = C_{insp} + C_m + C_{ref} - C_{rem} + C_s + C_{rw}f - P_{2nd} + C_q(Q_s^2 - Q_f^2 + Q_r^2)$$

$$\phi_3 = C_{insp} + C_m + C_s + C_p e_1 + C_{rw}f + C_p e_3 f$$

$$\phi_4 = C_p(b_1 + b_3 f)$$

$$\phi_5 = C_{im} + C_{ref} + C_p e_4 - P_{2nd} + P_i + C_q(Q_s^2 - Q_f^2)$$

$$\phi_6 = e_1 - e_2 + e_4 + e_3 f$$

$$\phi_7 = (b_1 - b_2 + b_4 + b_3 f)$$

$$\Omega_1 = (C_{it} + C_t - P_i + (C_{wd} + P_i)\lambda)$$

and

$$X = (\lambda - 1)(\phi_5 - (\phi_3 + C_p \phi_6) \rho)$$

$$Y = (\lambda - 1)(\phi_1 - C_p \phi_7 \rho)$$

Thus, we obtain

$$|H_1| = -\eta + 2\alpha(\phi_4 - Y\tau) < 0, \text{ if } \eta < -2\alpha(Y\tau - \phi_4)$$

$$|H_2| = -4C_q^2 Q^2 \alpha^2 - \gamma^2(\phi_4 - Y\tau)^2 + 2C_q(\eta(d + s\alpha + 3Q\gamma - \beta P_R) + 2\alpha(d + s\alpha + 2Q\gamma - \beta P_R)(B\tau - \phi_4)) > 0, \text{ if}$$

$$(Y\tau - \phi_4) >$$

$$\frac{1}{\gamma^2}(2\alpha C_q(d + \alpha s - \beta P_R + \gamma Q) +$$

$$\sqrt{2}\sqrt{C_q(d + s\alpha + 3Q\gamma - \beta P_R)(\gamma^2\eta + 2\alpha^2 C_q(d + \alpha s - \beta P_R + \gamma Q))})$$

$$|H_3| = d\alpha^2 + s\alpha^3 - P_R\alpha^2\beta + Q\alpha^2\gamma + \phi_4^2\beta^2(d + \alpha s - \beta P_R + \gamma Q) - 2d\beta\eta - 2s\alpha\beta\eta + 2P_R\beta^2\eta - 4Q\beta\gamma\eta - 2Y\alpha\beta C\tau + Y^2\beta^2(d + \alpha s - \beta P_R + \gamma Q)\tau^2 + 2\phi_4\beta(d + \alpha s - \beta P_R + \gamma Q)(\alpha - Y\beta\tau) < 0, \text{ if } \beta < \frac{-\alpha^2(d+s\alpha+Q\gamma)-2\beta^2\eta P_R+\beta(2(d+s\alpha+2Q\gamma)\eta+2YZ\alpha\tau+\alpha^2 P_R)}{(d+\alpha s-\beta P_R+\gamma Q)(Y^2\beta\tau^2+2\alpha\phi_4-2Y\beta\tau\phi_4+\beta\phi_4^2)}$$

$$|H_4| = -4B^2(d + \alpha s - \beta P_R + \gamma Q)^3 C_q \beta - g(-2C_q Q \beta + \gamma)^2 \eta + Y(d + \alpha s - \beta P_R + \gamma Q)(d + \alpha s - \beta P_R + \gamma Q)^2 (Y\gamma^2 + 4\beta C_q (X\alpha - Y(s\alpha + Q\gamma) - \alpha\Omega_1) + 4\beta^2 C_q (YQ^2 C_q + (Y\tau - \phi_4)(-X + Ys + \Omega_1))) - 2(d + \alpha s - \beta P_R + \gamma Q) C_q (g\alpha^2 - 2g\beta(\eta + Y\alpha\tau - \alpha\phi_4) + \beta^2 (g(-Y\tau + \phi_4)^2 + \eta(-X + Ys + \Omega_1)^2)) > 0, \text{ if } -4Y^2(d + \alpha s - \beta P_R + \gamma Q)^3 C_q \beta - g(-2C_q Q \beta + \gamma)^2 \eta - 2(d + \alpha s - \beta P_R + \gamma Q) C_q (g\alpha^2 - 2g\beta(\eta + Y\alpha\tau - \alpha\phi_4) + \beta^2 (g(-Y\tau + \phi_4)^2 + \eta(-X + Ys + \Omega_1)^2)) > +Y(d + \alpha s - \beta P_R + \gamma Q)^2 (Y\gamma^2 + 4\beta C_q (X\alpha - Y(s\alpha + Q\gamma) - \alpha\Omega_1) + 4\beta^2 C_q (YQ^2 C_q + (Y\tau - \phi_4)(-X + Ys + \Omega_1)))$$

Therefore, if the above condition is satisfied, H will be a negative definite Hessian matrix. Thus, the optimal decision can be obtained by taking the first partial derivatives of $\Pi^C(s, Q, P_R, \tau)$ with respect to s, Q, P_R and τ , respectively.

$$\frac{\partial \Pi^C}{\partial s} = -C_q Q^2 \alpha - s\eta - ((\Omega_1 - X)\alpha + Y(d + 2\alpha s + \gamma Q))\tau - \alpha\phi_3 + (d + 2\alpha s + \gamma Q)\phi_4 + P_R(\alpha + Y\beta\tau - \beta\phi_4)$$

$$\frac{\partial \Pi^C}{\partial Q} = -C_q Q(2d + 2s\alpha + 3Q\gamma) - (\Omega_1 - X + sY)\gamma\tau + (2C_q Q\beta + \gamma)P_R - \gamma\phi_3 + s\gamma\phi_4$$

$$\frac{\partial \Pi^C}{\partial P_R} = d + s\alpha + C_q Q^2 \beta + Q\gamma + (\Omega_1 - X + sY)\beta\tau + \beta(-2P_R + \phi_3 - s\phi_4)$$

$$\frac{\partial \Pi^C}{\partial \tau} = -(\Omega_1 - X + sY)(d + s\alpha + Q\gamma) - g\tau + (\Omega_1 - X + sY)\beta P_R$$

By setting the above equations equal to zero, [Proposition 1](#) is obtained.

In order to ensure $0 < Q^* < 1$, by substituting the optimal solution of Q in $0 < Q^* < 1$, we solve to get the following expression:

$$3C_q \gamma > \sqrt{C_q(C_q(d + s\alpha - \beta P_R)^2 + 3\gamma^2(-(\Omega_1 - X + sY)\tau + P_R - \phi_3 + s\phi_4))} - C_q(d + s\alpha - \beta P_R)$$

Moreover, to ensure $0 < \tau^* < 1$, we solve $0 < \tau^* = \frac{-(-\Omega_1 + X - sY)(d + \alpha s + \gamma Q) - (\Omega_1 - X + sY)\beta P_R}{g} < 1$, to result in the following expression:

$$g > (\Omega_1 - X + sY)\beta P_R - (-\Omega_1 + X - sY)(d + \alpha s + \gamma Q)$$

Appendix B

Proof of [Proposition 2](#)

By taking the first-order and the second order derivatives of Π_R with respect to P_R we will have

$$\frac{\partial \Pi_R}{\partial P_R^M} = d + \alpha s - \beta P_R + \gamma Q + \beta P_M - 2\beta P_R = 0$$

$$H^R = \left(\frac{\partial^2 \Pi_R}{\partial P_R^2} \right) = -2\beta$$

It is proved that the Hessian matrix of Π_R is a negative definite for all values of P_R if $-2\beta < 0$. Also, the optimal value of P_R can be obtained by setting the first-order derivatives equal to zero.

Appendix C

Proof of Proposition 3

By taking the first-order and the second order derivatives of Π_C with respect to τ we will have

$$\frac{\partial \Pi_C}{\partial \tau^M} = -g\tau - (d + \alpha s - \beta P_R + \gamma Q)\Omega_1 = 0$$

$$H^C = \left(\frac{\partial^2 \Pi_C}{\partial \tau^2} \right) = -g$$

It is proved that the Hessian matrix of Π_C is a negative definite for all values of τ if $-g < 0$. Also, the optimal value of τ can be obtained by setting the first-order derivatives equal to zero. Moreover, to ensure $0 < \tau^* < 1$, by substituting the optimal solution of τ^* in $0 < \tau^* < 1$, we solve to obtain the following condition:

$$g > (\beta P_R - d - \alpha s - \gamma Q)\Omega_1$$

Appendix D

Proof of Proposition 4

The Hessian matrix of $\Pi_M(s, Q, P_M)$ is given by

$$H^M = \begin{pmatrix} \frac{\partial^2 \Pi_M}{\partial s^2} & \frac{\partial^2 \Pi_M}{\partial s \partial Q} & \frac{\partial^2 \Pi_M}{\partial s \partial P_M} \\ \frac{\partial^2 \Pi_M}{\partial Q \partial s} & \frac{\partial^2 \Pi_M}{\partial Q^2} & \frac{\partial^2 \Pi_M}{\partial Q \partial P_M} \\ \frac{\partial^2 \Pi_M}{\partial P_M \partial s} & \frac{\partial^2 \Pi_M}{\partial P_M \partial Q} & \frac{\partial^2 \Pi_M}{\partial P_M^2} \end{pmatrix}$$

$$= \begin{pmatrix} -\eta + 2\alpha(\phi_4 - Y\tau) & -2C_q Q\alpha + \gamma(\phi_4 - Y\tau) & \alpha \\ -2C_q Q\alpha + \gamma(\phi_4 - Y\tau) & -4C_q Q\gamma - 2C_q(d + \alpha s - P_R\beta + Q\gamma) & \gamma \\ \alpha & \gamma & 0 \end{pmatrix}$$

In order to prove the concavity of the manufacturer's profit, we show that $x.H^M.x < 0$ where $x = [s, Q, P_M]$. By solving $x.H^M.x < 0$, we have the following expression:

$$C_q > -\frac{\gamma^2 \eta}{2\alpha^2(d + \alpha s - P_R\beta + Q\gamma)}$$

Moreover, to ensure $0 < Q^* < 1$, by substituting the optimal solution of Q^* in $0 < Q^* < 1$, we solve to obtain the following condition:

$$C_q > \frac{\sqrt{C_q(C_q(d + \alpha s - P_R\beta)^2 + 3\gamma^2(P_M - \phi_3 + s\phi_4 - (X + sY)\tau)) - C_q(d + \alpha s - P_R\beta)}}{3\gamma}$$

By integrating the above two conditions, we obtain

$$C_q > \max \left\{ -\frac{\gamma^2 \eta}{2\alpha^2(d + \alpha s - P_R\beta + Q\gamma)}, \frac{\sqrt{C_q(C_q(d + \alpha s - P_R\beta)^2 + 3\gamma^2(P_M - \phi_3 + s\phi_4 - (X + sY)\tau)) - C_q(d + \alpha s - P_R\beta)}}{3\gamma} \right\}$$

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