

# Dual-channel remanufacturing closed-loop supply chains under carbon footprint and collection competition

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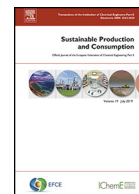
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## Dual-channel remanufacturing closed-loop supply chains under carbon footprint and collection competition

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## ABSTRACT

Due to economic and environmental advantages, transferring from linear systems into circular economies has been accelerated, especially in developed countries, which affects companies' relations. Among different tools and methodologies, the closed-loop supply chain (CLSC) model as an established approach has shown its efficiency in reflecting these relations regarding the consumers' behavior. Because of the complexity, limited studies have considered the effects of different factors simultaneously on different CLSC network designs. This is the first attempt to study the effects of carbon emission and remanufacturing simultaneously on a dual-channel in both forward and reverse logistics, while there is competition on collection. Accordingly, a novel format for the demand function is suggested and employed. The decisions regarding the optimal pricing and collection strategies of CLSCs were investigated, within which the manufacturer is responsible for the remanufacturing process and selling the remanufactured products directly to the customer through the online channel. In contrast, new products are sold via the traditional retailer channel, imposing relevant costs. We explore the effect of different dual-collection settings when there is competition between collector parties under three possible options (i.e., Manufacturer-Retailer, Manufacturer-Third-party, and Retailer-Third-party). The considered demand for both new and remanufactured products addresses consumers who have different willingness to choose the remanufactured items and are sensitive to the produced products' carbon footprint. The behavior of the formulated CLSC models is studied by game theory regarding decision variables, and each player's profit is discussed through systematic comparison. We analytically show that considering all the effects, third-party entry is not in the manufacturer's interest. The findings show that consumers' willingness to choose remanufactured products is generally more influential on prices and profits than their sensitivity to the carbon footprint.

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## 1. Introduction

Global warming, environmental pollution, and climate changes are the main effects of greenhouse gases, and particularly, carbon dioxide. They are identified as common problems of the international community (Farquharson et al., 2017; Gopalakrishnan et al., 2020; Lee and Tang, 2018). Thus, several efforts (e.g., the Kyoto Protocol, the Copenhagen Climate Summit, the Paris Agreement, and the European Union Emissions Trading Scheme) have been made to establish policies to mitigate carbon emission. These plans have

caused many countries to adopt and enact carbon emission policies examined by scientists via the present approaches in the sustainable supply chain (SC) and circular economy (Fahimnia et al., 2013; Mazahir et al., 2019; Van Wassenhove, 2019). Therefore, there is an increasing trend in public authorities' and shareholders' awareness regarding the harmful and destructive effects of carbon emissions. For example, it has been shown that highly educated Chinese consumers have more willingness to pay (WTP) for low-carbon products (Shuai et al., 2014). Furthermore, the consumer's perspective, which forms the demand market, is changing. A survey on consumers' perceptions of carbon-labeled electrical and electronic products in Chinese first-tier cities (Xu and Lin, 2021) shows that almost 86% of respondents are willing to pay more for carbon-labeled products. An online questionnaire among Brazilian consumers indicated that 65% sought to buy generic products from sustainable companies (Garcia et al., 2019). Therefore, companies

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## Nomenclature

Symbole	Definition
$n$	new products
$r$	remanufactured products
$m$	Manufacturer
$e$	Retailer
$t$	Third-party
<i>Parameters</i>	
$c_m$	The unit production cost of a new product from raw materials by the manufacturer
$c_r$	The unit cost of remanufacturing a used product
$s$	Fixed cost of offline selling by the retailer
$a$	Basic market demand
$D_n^e$	Demand rate of the new product through the retailer channel
$D_r^m$	Demand rate of the remanufactured product through the manufacturer channel
$\mu$	Share of the basic demand to the direct channel for selling the remanufactured product
$\lambda_1$	Sensitivity factor of the retail price for the new product in the retailer channel
$\lambda_2$	Sensitivity factor of the online price for the remanufactured product in the manufacturer channel
$e(\tau_i)$	Carbon footprint per unit product depending on the collection rate
$e_n$	Carbon emissions released due to producing new products from fresh raw materials
$e_r$	Reduction of carbon emissions due to remanufacturing
$K$	Cost coefficient of emission reduction
$A_i$	Average recycling price/cost for used products collected by the collector for $i = m, e, t$
$b$	Average recycling price for used products paid by the manufacturer to the collector
$C(e)$	Carbon emission reduction cost
$I_i$	Investment of collector party $i = m, e, t$ to collect the cores
$0 \leq \alpha \leq 1$	The competing coefficient between the two collection channels
$0 < \chi < 1$	Customers' willingness to choose the remanufactured product as the price difference increases
$0 \leq \gamma \leq 1$	The consumer's sensitivity to the carbon footprint of the product
$C$	Scaling parameter of the collection costs
<i>Decision variables</i>	
$p_n^e$	Price of the new product through the retailer channel
$p_r^m$	Price of the remanufactured product through the manufacturer channel
$w$	Wholesale price of the new product to the retailer by the manufacturer
$\tau_i$	Collection rate by the collector party $i = m, e, t$
<i>Other notations</i>	
$\Pi_i^j$	Profit function of the related party $i$ for the case $j$

need to understand it and take action in setting consumer's demand.

Although we are far from an ideal situation, consumers' behavior is gradually improving, and they are becoming increasingly environmentally conscious (Cheung and To, 2019; Kautish et al.,

2019; Xu et al., 2020). A study in Hong Kong showed that consumers' attitudes toward purchasing low-carbon beverages were significantly influenced by their awareness (Wong et al., 2020). In the European Union (EU), 26% of consumers frequently purchase green products, while 54% of EU consumers purchase them occasionally (Eurobarometer, 2013). From the BBMG Conscious Consumer Report (www.bbm.com), 51% of Americans are willing to pay more for environmentally friendly products and generally believe they can make a difference through their purchases from socially responsible companies. Many developed countries in the EU and North America adopt carbon footprint labeling on their food packaging (Greibitus et al., 2016; Hartikainen et al., 2014), and the public participates in the low-carbon lifestyle and has a preference to buy low-carbon products. It can not only affect the market demand but also be used as a source of competitive advantage for the companies if they take appropriate actions through the SC. For instance, Mostafa (2016) demonstrated that WTP for eco-labeled products in Egypt is expected to be linked to green purchase behavior; thus, policymakers may use such link to design better marketing strategies focusing on promoting green products. Investigating consumers' change toward more sustainable consumption patterns and carbon emissions saved in production that impact consumers' behavior are suggested as valuable topics that require further exploration (Rondoni and Grasso, 2021).

In 2008, one of the most extensive research efforts ever conducted in SC management by Accenture (www.accenture.com) showed that only 10% of companies actively model their SC carbon footprints and implement successful sustainability initiatives, and 37% of SC executives are unaware of the level of SC emissions in their SC network (Barere and Corcoran, 2009; Berns et al., 2009). Although these figures have improved during the last decade and many practices have been identified, further efforts are still required to measure the performance. It is necessary to enhance the knowledge of SC executives and managers on the importance of sustainability when planning strategies. The closed-loop supply chain (CLSC) field introduces approaches to abate carbon emissions that help the organization act sustainably (Guide Jr and Van Wassenhove, 2009; Guide and Van Wassenhove, 2003). It integrates activities in both forward and reverse SCs (Paksoy et al., 2011). Beneficial to the environment, but complex in nature, CLSC has understandably been a study topic for many researchers (Fu et al., 2021).

Reverse logistics is an opportunity for industries to redesign their networks and collect products that add value to SC (Shekarian et al., 2016). However, it can also induce competition between market players (Li, X. et al., 2019; Wu, 2015). Moreover, recycling and remanufacturing used products reduce negative impacts on the environment by decreasing carbon emissions and saving more resources that create a good corporate perspective and improve enterprises' profits (Subramanian and Subramanyam, 2012). In this regard, Liao and Li (2021) analyzed the overall carbon emissions saved by remanufacturing printers through a CLSC and subsequently calculated the environmental benefit accordingly. As another example, the potential economic benefit of closed-loop recycling of end-of-life (EoL) silicon solar photovoltaic modules was identified by Deng et al. (2021), inducing a 20% reduction in manufacturing costs. Carbon emission in the forward direction while (re)producing and selling the products could also be decreased. In contrast to traditional methods, online shopping is an important factor affecting carbon emission (Wu et al., 2021) and contributing to its reduction (Zhang et al., 2021). In the United States (US), it was confirmed that delivery services and operations as elements of online shopping foster a more sustainable urban environment (Jaller and Pahwa, 2020). According to Rosqvist and Hiselius (2016), a predicted increase in online shopping behavior in 2030 in Sweden would result in a 22%

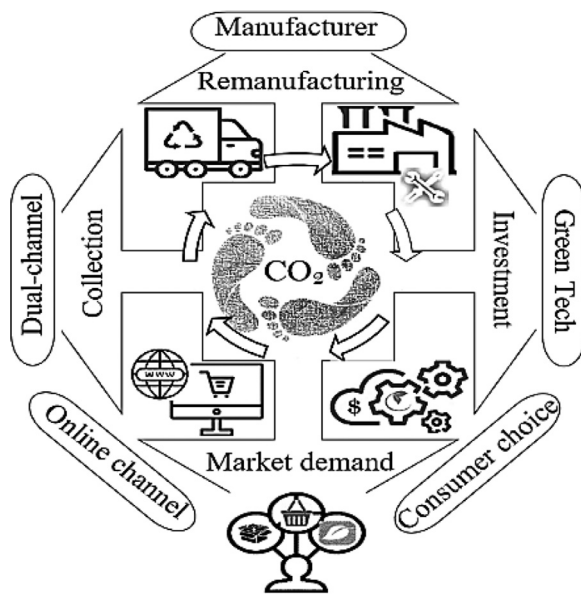


Fig. 1. Conceptual framework of the investigated closed-loop supply chains

decrease in CO<sub>2</sub> emissions related to shopping trips compared to 2012. It can decrease carbon emissions, for example, by considering the pollutants caused by passengers' vehicles (Belavina et al., 2017; Cachon, 2014). Investment of the original equipment manufacturer (OEM) in new green production technologies (Aflaki and Netessine, 2017; Hu et al., 2015; Kök et al., 2018) is another approach in tackling emission issues. For instance, in IBM, a carbon heat map has been attempted to display the effect of carbon emissions on a specific SC (Yang and Xu, 2019).

We believe that this study is the first to develop models interfacing CLSC concepts and consumers' behaviors on market demand, while the carbon footprint negatively impacts the demand for new and remanufactured products. The models were formulated based on online shopping and green technology to deal with carbon reduction. Moreover, there is competition on collection channels between collector parties. Three different structures were designed to investigate and reply to the following questions. Fig. 1 shows the conceptual framework of the study.

- What are the optimum collection rates, prices of new and remanufactured products, and wholesale prices of new products in each scenario?
- Which scenario is the best for each party's profit?
- How are consumer behavior (willingness in choosing the remanufactured products and sensitivity to the carbon footprint) on decision variables and each party's profits and collection rates?
- How can competition on collection affect each model's collection rates, profits, and decision variables?

The remainder of this study is structured as follows: Section 2 reviews the literature to find a gap and make a comparative discussion of previous studies. Section 3 describes the problem by explaining the assumptions and formulating the investigated issues. Section 4 presents the solution methodology for finding the optimal values. Section 5 discusses the results, numerically compares different policies, and presents the managerial insights. Finally, Section 6 presents the conclusion and future research.

## 2. Literature review

We developed models to investigate the effects of remanufacturing, carbon emission, and dual-channels simultaneously. There-

fore, these three streams of research in the literature are reviewed accordingly. The contributions of related studies regarding the present research are summarized and compared in Table 1.

### 2.1. Remanufacturing

Researchers and managers extensively agree that OEMs, which have opportunities to produce both new and remanufactured products, are better regarding centrally controlling their manufacturing and remanufacturing activities (Zhou et al., 2013). However, under a game-theoretical setting, there are studies that extensively discussed the role of manufacturer (she)<sup>1</sup> and third-party reverse logistics provider (TRLP) in remanufacturing EoL or end-of-use (EoU) products (Chen and Chang, 2012) and close the loop. Based on a Stackelberg game (Section 3.1), Yan and Sun (2012) modeled a rebate-punish contract between manufacturer as remanufacturer and TRLP, studying the impacts of environmental legislation on scrap recycling and stochastic price-dependent demands. Huang and Wang (2017) considered hybrid remanufacturing in which she collects and remanufactures a fraction of used products and licenses the distributor or TRLP to remanufacture the rest. Zhang, Y. et al. (2020) and Zhang, F. et al. (2020) studied remanufacturing modes, including outsourced and authorized remanufacturing, for a competitive SC. Meng et al. (2020) investigated the optimal government consumption subsidy policy and its impact on the operation of CLSC, where an OEM produces new products, while a TRLP remanufactures the used products. Huang and Wang (2020) investigated the interaction between information sharing and learning effects with OEM remanufacturing and TRLP remanufacturing under technology licensing. Table 1 determines which party implements the remanufacturing process and sells remanufactured products to the consumers. It shows that in most of the reviewed works and also our suggested models, the manufacturer is the dominant party responsible for remanufacturing. As discussed, this is an efficient way.

Remanufacturing models can be extended by adding other parties, such as suppliers, to the model. For instance, Zhou et al. (2013) and Xiong et al. (2013) considered a decentralized CLSC in which one OEM can purchase new components from one supplier to produce new products and collect used products from consumers to produce remanufactured products. He (2015) studied acquisition pricing and remanufacturing decisions under both demand and supply uncertainties. Jin et al. (2017) developed a game-theoretical model to revisit the impact of TRLP remanufacturing on a forward SC in which one OEM purchases critical components from one dominant supplier. Wu and Zhou (2019) studied the effects of a uniform pricing policy in a CLSC with TRLP remanufacturing and government permissions to the supplier to charge buyer-specific wholesale prices. Xiang and Xu (2020) proposed a two-stage remanufacturing CLSC model comprising a manufacturer, a TRLP who invests in big data marketing activities, and a supplier based on differential game theory. Considering that both the manufacturer and the remanufacturer invest in green manufacturing processes, Toktaş-Palut (2021) developed an integrated two-part tariff contract so that all SC members act rationally following the centralized solution. To compare the performance of the suggested CLSC models, we added a third-party to the developed model responsible for collection while the manufacturer pays it.

Remanufacturing systems are addressed based on the competition between two parties. Wu (2015) verified the circumstances in which OEMs should strategically provide incentives to recycle markets in competing with remanufacturers. The optimal price

<sup>1</sup> Hereafter, She/her refer to the manufacturer.

**Table 1**  
A comparison of this research with previous studies in the literature.

Reference	Remanufacturing consideration		Different price of new and remanufactured products	Carbon consideration		Channels structure Different channels for selling new and remanufactured items	Competition on dual collection channels
	Responsible party for selling remanufactured item	Responsible party for remanufacturing		Consumers' sensitivity to carbon footprint	Carbon cost function		
Modak and Kelle (2019)							
Wang, N. et al. (2020)							✓
Mondal and Giri (2020b); Wu et al. (2018)	Two competing retailers	Manufacturer					
Wei and Zhao (2011)	Two competing retailers	Manufacturer	✓				
Hosseini-Motlagh et al. (2020b)	Two competing dealers	Manufacturer					✓
Chen and Chang (2012)	Third-party and OEM*	Third-party and OEM	✓			✓	
Dong et al. (2019); Dou and Cao (2020); Gao et al. (2016); Hong et al. (2020); Hong et al. (2013); Shi et al. (2015); Shu et al. (2018); Wan and Hong (2019); Yan and Sun (2012); Zerang et al. (2018)	Retailer	Manufacturer					✓
He, Q. et al. (2019); Huang et al. (2013); Liu et al. (2017); Wan (2018)	Retailer	Manufacturer	✓				
Gan et al. (2019); Liu et al. (2020); Rezayat et al. (2020); Tang et al. (2020); Wen et al. (2020)	Retailer	Manufacturer	✓				
Wang and Wu (2020)	Retailer	Manufacturer		✓			
Yang et al. (2020)	Retailer	Manufacturer			✓		
Xing et al. (2020)	Retailer	Manufacturer		✓			✓
Li et al. (2017)	Retailer	Manufacturer		✓	✓		✓
He (2015); Xiang and Xu (2020)	Manufacturer	Manufacturer					
Huang et al. (2020); Jin and Zhou (2020); Xiong et al. (2013); Yenipazarli (2016)	Manufacturer	Manufacturer	✓				
Zhang et al. (2018)	Manufacturer	Manufacturer		✓	✓		
Yi et al. (2016)	Retailer	Retailer	✓				
Xu and Wang (2018)	Retailer	Retailer		✓	✓		
Wang, Y. et al. (2020)	Remanufacturer	Remanufacturer		✓	✓		
Wu (2015)	Remanufacturer	Remanufacturer	✓			✓	✓
Jin et al. (2017); Meng et al. (2020); Wu and Zhou (2019)	Third-party	Third-party	✓			✓	
He, P. et al. (2019)	Third-party	Manufacturer	✓			✓	
Zhou et al. (2013)	OEM's Rem division	OEM's Rem division	✓			✓	
Arshad et al. (2018); He et al. (2016)	Traditional retailer and an online retailer	Manufacturer					
Giri, et al. (2017); Kong et al. (2017); Shi et al. (2020); Taleizadeh et al. (2016); Wang, J. et al. (2020); Xiao et al. (2020); Xie et al. (2018)	Retailer and Online by Manufacturer	Manufacturer					
Yang et al. (2018b)	Retailer and Online by Manufacturer	Manufacturer			✓		
Yang et al. (2018a)	Retailer and Online by Manufacturer	Manufacturer		✓	✓		
Zheng et al. (2017)	Retailer and Manufacturer	Manufacturer					
Mondal and Giri (2020a)	Retailer and Manufacturer	Manufacturer	✓			✓	✓
Reimann et al. (2019)	Retailer	Manufacturer or Retailer	✓				
Jena and Sarmah (2014)	Retailer	Two Manufacturers					✓

(continued on next page)



Table 1 (continued)

Reference	Responsible party for selling remanufactured item	Responsible party for remanufacturing	Different price of new and remanufactured products	Carbon consideration Consumers' sensitivity to carbon footprint	Carbon cost function	Channels structure for selling new and remanufactured items	Competition on dual collection channels
Huang and Wang (2017)	Distributor	Manufacturer and Third-party, Manufacturer and Distributor					
Taleizadeh et al. (2019)	Retailer	Manufacturer and Third-party, Manufacturer and Distributor		✓	✓		
Wang et al. (2019)	Retailer	Manufacturer and/or remanufacturer	✓				✓
Huang and Wang (2020)	Retailer	OEM or Third-party					
Zhang, F. et al. (2020)	OEM or Authorized remanufacturer	Authorized remanufacturer	✓			✓	
Zhang, Y. et al. (2020)	OEM(s) and/or Third-party (s)	OEM(s) and/or Third-party (s)	✓			✓	
Formulated models	Online by Manufacturer	Manufacturer	✓	✓	✓	✓	✓

\*OEM: original equipment manufacturer

ing decision problems of a CLSC with two competitive retailers and a manufacturer are explored, in which the remanufacturing and collecting costs are fuzzified (Wei and Zhao, 2011) or when remanufacturing costs are disrupted (Wu et al., 2018). Wang et al. (2019) studied competition in the recycling market between a manufacturer and remanufacturer or retailer and remanufacturer. He, Q. et al. (2019) investigated the channel structure in the competitive collection to achieve optimal recovery efficiency. Hosseini-Motlagh et al. (2020b) formulated a new function for the supply of used products based on the service competition between two dealers, and the manufacturer's economic incentives suggested to the dealers to persuade them to return the collected products. We propose CLSC models where competition simultaneously exists on the collection and selling market between the responsible parties.

Other factors are researched in remanufacturing models that are solved based on game models. Shi et al. (2015) examined the collection's responsibility-sharing under three different reverse channels: retailer collection, manufacturer collection, and third-party collection. Zerang et al. (2018) and Dong et al. (2019) analyzed the impacts of marketing and collection efforts on the remanufacturing process, respectively. Some studies have developed remanufacturing CLSC models with different types of contracts (Huang et al., 2020; Rezayat et al., 2020). Some review studies have taken different aspects of SC contracts, such as the classification of coordination contracts in forward and reverse SCs (Govindan et al., 2013; Guo et al., 2017; Krapp and Kraus, 2019). SC contracting mechanisms with different information settings are reviewed and classified by Shen et al. (2019). Jin and Zhou (2020) and Tang et al. (2020) dealt with finding optimal warranty policies. Hong et al. (2020) embedded value-added services into remanufacturing models. Hosseini-Motlagh et al. (2020a) extended the previous literature by proposing a cost–tariff contract in CLSCs with the simultaneous effects of remanufacturing and energy-saving efforts on environmental sustainability. Reimann et al. (2019) studied process innovation's ability to lower variable remanufacturing cost. Recently, Bakhshi and Heydari (2021) addressed a two-echelon reverse SC to investigate the performance of a put option contract as a risk-sharing approach to mitigate remanufacturing capacity uncertainty. For a more comprehensive review of essential factors, the reader can refer to a recent review paper by Shekarian (2020).

The models were investigated by comparing different game-based scenarios. For example, Gao et al. (2016) presented a comprehensive discussion on the remanufacturing CLSC under different channel power structures (i.e., manufacturer/retailer Stackelberg and vertical Nash) when market demand is sensitive to collection effort, sales effort, and the price. Liu et al. (2020) investigated the effects of different power structures, the quality difference among used products, and the price difference between new and remanufactured products on the pricing policies of a multi-echelon CLSC. Wen et al. (2020) developed game models to explore price and collection rate decisions in a CLSC, considering heterogeneous consumers with environmental responsibility. In this study, there is a distinction between the prices of new and remanufactured products. The proposed models are solved based on Stackelberg scenarios.

## 2.2. Carbon emission

Another feature we considered in the developed models is the effects of carbon emission. We can generally categorize the policies on carbon emission reduction into two parts: cap-and-trade regulation (CATR) and investment in low-carbon production technologies. Under the background of the first policy, if the total carbon emissions exceed (fall behind) a critical value, the producer (i.e., manufacture or remanufacturer) would be punished (rewarded), usually by the government or social planner through tax and subsidy approaches. In this regard, Mondal and Giri (2020b) and Wang and Wu (2020) established strategies for carbon emission reduction and used product collection. Li et al. (2014) and Wang, Y. et al. (2020) analyzed the impact of carbon subsidy on remanufacturing CLSC. Under carbon tax regulation, Yenipazarli (2016) and Dou and Cao (2020) measured the environmental and economic performance on the optimal production and pricing decisions of CLSCs, where remanufacturing is implemented through the reverse channels. They explored the impacts of the emission intensities of new and remanufactured products on the entire emissions. We followed the second policy to reduce carbon emissions, assuming that the manufacturer invests by applying new technology. Table 1 shows the relevant studies, under the column called “carbon cost function.”

Shu et al. (2018) discussed the simultaneous effects of CATR and corporate social responsibility (CSR) on recycling and remanufac-

turing decisions. Based on CATR, Zhang et al. (2018) studied joint dynamic green innovation policy and pricing strategies in a hybrid manufacturing and remanufacturing system with a differential game. Modak and Kelle (2019) suggested that the carbon footprint per unit product depends on the recycling rate, and they integrated the CSR investments into a CLSC, where the stochastic demand depends on the sales price and social work donation under a carbon emissions tax. Yang et al. (2020) addressed a remanufacturing CLSC under CATR, where the collecting operations can be conducted by a manufacturer, retailer, or TRLP. Taleizadeh et al. (2019) used both mentioned policies to reduce carbon emissions.

Some models analyzed the interaction of consumer behavior concerning carbon emission impact and remanufacturing. He et al. (2016) evaluated the impact of consumer free-riding on carbon emissions in a product's life cycle across a dual-channel CLSC (DCCLSC) and assessed the effect of a governmental e-commerce tax on carbon emissions. Xu and Wang (2018) focused on a two-period CLSC incorporating the consumer's low-carbon and remanufactured preference into the market demand, considering centralized and decentralized models comprising one single manufacturer and retailer. Gan et al. (2019) proposed a revenue-sharing contract, CATR, and consumers' different WTP for remanufactured products. Furthermore, the impact of revenue-sharing and cost-sharing contracts offered by a retailer on emission reduction efforts and firms' profitability is discussed under the Nash bargaining model (Li, T. et al., 2019). In this study, the influence of carbon on consumers' behavior via the joint effect of collection effort and demand function is unprecedentedly studied.

### 2.3. Dual-channels

Developing DCCLSC is another stream of research regarding this study's topic. In a dual-channel, two parties are jointly involved in forward and/or reverse channels. For example, she can contract the collection of used products to a retailer and third-party jointly, or collect through a dual-channel either by a retailer or third-party (Arshad et al., 2018; Hong et al., 2013). A special CLSC model with a dual-recycling channel within the framework of game theory is discussed by Yi et al. (2016) to explore how the remanufacturer should properly allocate collection efforts to the retailer and third-party. Giri et al. (2017) designed a game-based CLSC with the forward dual-channel where she sells a product to customers through the traditional retail channel and e-tail (internet) channel, and reverse dual-channel where the used items are collected for remanufacturing through the traditional TRLP and e-tail channel. Shi et al. (2020) investigated the effect of integration in DCCLSCs either forwardly or reversely. They discussed which direction of integration brought more profit for the integrated entities.

A competition can be considered via a dual-channel, and game theory is an appropriate tool to investigate this situation. Huang et al. (2013) investigated the optimal strategies of a remanufacturing CLSC with a dual recycling channel, where the retailer and TRLP competitively collect used products. Jena and Sarmah (2014) studied the competition issue in a CLSC comprising two manufacturers who compete to sell their new products and collect the used products for remanufacturing through a common retailer. Zheng et al. (2017) examined the effect of forward channel competition and power structure on DCCLSC. Liu et al. (2017) investigated competition between dual recycling channels (i.e., OEM and retailer dual collecting model, retailer and TRLP dual collecting model, and OEM and TRLP dual collecting model). Mondal and Giri (2020a) constructed a competition between a manufacturer and retailer to collect used products, employing a dynamic manufacturer–retailer Stackelberg game. Wang, N. et al. (2020) explored consumer behavior's influence on competitive dual-collecting, including the retailer and

TRLP and the manufacturer and TRLP. He, P. et al. (2019) considered a DCCLSC where she can sell new products directly and distribute remanufactured products through the TRLP, or sell remanufactured products directly and distribute new products via the retailer.

Some models have examined the effects of carbon emissions through DCCLSC using game theory. Li et al. (2017) investigated the influences of different game structures on the optimal decisions and performance of a low-carbon CLSC with price-and carbon emission level dependent demand. Wan (2018) considered a dual collection in different CLSC power structures where she sells the new and remanufactured products through the retailer and obtains a low-carbon subsidy allocated by the government for each unit remanufactured product. Moreover, remanufacturing in a DCCLSC under CATR is discussed (Yang et al., 2018a; Yang et al., 2018b). Xing et al. (2020) constructed a recycling and remanufacturing CLSC comprising two competing third-party recyclers with risk-aversion characteristics, CATR, and consumers' low-carbon awareness.

Furthermore, other problems have been addressed in DCCLSC studies. Taleizadeh et al. (2016) modeled several marketing efforts (manufacturer as an investor, retailer as an investor, and the centralized CLSC system) as DCCLSC models. Revenue-sharing contracts are designed for DCCLSCs, where the products are sold online and offline (Kong et al., 2017; Xie et al., 2018). Additionally, Wu et al. (2020) constructed a revenue-sharing contract to optimize the benefits of SC members under decentralized decision-making between a recycling center and TPR, considering service level. Stackelberg models are analyzed to find the optimal pricing and recycling policies for a CLSC with retailer and third-party dual collection channels in which the transfer prices paid by the manufacturer to the two recyclers are either uniform or different, and government subsidies are provided with either the manufacturer or the two recyclers (Wan and Hong, 2019). Wang, J. et al. (2020) considered product customization given that she sells customized products through her online channel, sells standard products through both an online and a retail channel, and both the manufacturer and the retailer can simultaneously collect the used products. Xiao et al. (2020) constructed a retail channel model and a dual-channel model under trade-in scenarios.

Two distinguished factors from the channel perspective, which consider separate channels for selling new and remanufactured products and competition on dual collection channels, are represented in the last two columns of Table 1.

### 2.4. Research gaps

Table 1 categorizes the literature based on each work's contribution to different aspects of carbon consideration (see columns 5 and 6) and channel structure (see columns 7 and 8). Some studies included only one aspect of carbon consideration (Wang and Wu, 2020; Yang et al., 2018b) or channel structure (Chen and Chang, 2012; Wang et al., 2019). Although some studies have considered both specifications related to channel structure (Mondal and Giri, 2020a; Wu, 2015) or carbon consideration (Li et al., 2017; Taleizadeh et al., 2019; Wang, Y. et al., 2020; Xu and Wang, 2018; Yang et al., 2018a; Zhang et al., 2018), this is the first attempt to concurrently study the effects of all these specifications in remanufacturing CLSC models.

The last row in Table 1 shows the differences between the models developed in the present and previous studies. Recently, Shekarian and Flapper (2021) illustrated different CLSC models designed based on game theory and the employed features implemented through the literature. They provided a big picture comparing 196 different models derived from 230 studies until 2020. Considering previous studies, this study specifically investigated the interaction of the carbon footprint on customers via separate

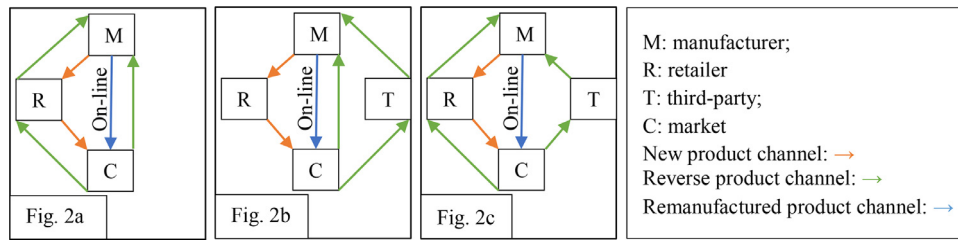


Fig. 2. Structures of the formulated the closed-loop supply chain models

demand functions for new and remanufactured products uniquely. In this context, the level of carbon footprint is dependent on the collection rate. Additionally, this study is among the few that discuss the effects of competition on both forward and reverse directions simultaneously.

### 3. Methods

#### 3.1. Description of the models

We are interested in analyzing consumers' environmental behavior in CLSCs given dual-collection channels under competition between the collector parties. Three CLSC models were introduced considering consumers' sensitivity to the product's carbon footprint and their willingness to choose the remanufactured product as the price difference increased. In the developed models, we assumed that the manufacturer was responsible for remanufacturing and selling the remanufactured printer products via an online channel. The retailer in the offline channel sells the new printer products. From the literature, there are reasons to consider this structure as below (Borenich et al., 2020; Giri et al., 2017; Kong et al., 2017; Shi et al., 2020; Wang, J. et al., 2020; Yang et al., 2018a).

- 1 One of the main reasons manufacturers, such as HP, prefer to sell remanufactured items in an online outlet store is issues regarding cannibalization.
- 2 This structure creates strategic interactions with the retailer because the retailer can exert effort to reduce the volume of returns, and hence reduce the volume of remanufactured products sold by the manufacturer. Accordingly, the retailer can control the new product price to compete with the manufacturer's remanufactured products.
- 3 In some industries, such as the electronics industry, direct sales of new products by manufacturers to consumers constitute a relatively small portion of their revenues. For instance, in 2016, HP obtained almost 80 percent of its revenues worldwide<sup>2</sup> through its channel partners (retailers). Another example is Philips, which earns only 0.3% of total sales in the DACH region (Austria, Germany, and Switzerland) by directly selling the new products<sup>3</sup>.
- 4 The existence of the online store persuades the retailer to lower the retail price significantly, thereby increasing sales, while the manufacturer hardly needs to change its wholesale price.

The related structures are illustrated in Fig. 2. A comprehensive review of recent structures is illustrated by Shekarian and Flapper (2021). The proposed models are formulated by employing three Stackelberg games to maximize CLSC members' profits. It is a strategic game in economics in which at least one player is defined

as the leader, who can make a decision and commit a strategy before other players who are defined as followers. Stackelberg games are widely used for sustainable optimization (Pakseresht et al., 2020).

#### 3.2. Assumptions

The models were developed under the following assumptions:

**Assumption 1.** There are two types of products: new and remanufactured printer products. They are sold through separate channels by the retailer and manufacturer with price  $p_n^e$  and  $p_r^m$ , respectively, in which  $p_r^m < p_n^e$ ,  $w < p_n^e$  and  $w$  is the wholesale price of the new product. There are similar studies that considered different prices for new and remanufactured products (Jin et al., 2017; Yan et al., 2018).

**Assumption 2.** Collection rate ( $0 \leq \tau_i \leq 1$ ) measures the reverse channel performance denoting the fraction of current generation products remanufactured from returned units. We can model  $\tau_i$  as a function of the product collection effort, which is denoted by  $I_i$ , the investment in collection activities. According to Savaskan et al. (2004), when there is one collector party, we can employ the cost structure  $\tau_i = \sqrt{I_i/C}$  to characterize the diminishing returns to investment. In this equilibrium,  $C$  is a big scaling parameter. This formula is prevalent in the literature, including advertising response models of consumer retention and product awareness, and in salesforce effort response models in the marketing literature.

In our cases, the two parties compete simultaneously to collect the cores from the market (Liu et al., 2017; Wang et al., 2019). This competition exists in three cases between the manufacturer and retailer (Fig. 2a), manufacturer and third-party (Fig. 2b), and retailer and third-party (Fig. 2c). Therefore, the collection rate of one party can be reasonably formulated as a monotonic increasing function of its own investment and as a monotonic decreasing function of the investment of its competitor (Huang et al., 2013). For example, if the manufacturer and third-party compete to collect the returned products, we can show the relevant collection rates as below. In this situation, the competition intensity is shown as  $0 \leq \alpha \leq 1$ . The scaling parameter  $C$  is assumed to be large enough to guarantee that the total collection rate  $\tau_t$  is less than one (i.e.,  $0 \leq \tau_i + \tau_j = \tau_t \leq 1$ ). We can use similar forms for other suggested structures.

$$\tau_m = \sqrt{\frac{I_m - \alpha I_t}{C}} \quad \text{and} \quad \tau_t = \sqrt{\frac{I_t - \alpha I_m}{C}}$$

**Assumption 3.** The manufacturer is responsible for remanufacturing, supposing that the unit cost of producing end products from the collected cores to produce the remanufactured items is lower than those from new materials (i.e.,  $c_r < c_m$ ). This assumption reflects the primary incentive of the manufacturer to remanufacture the returned items and implies that savings from materials and the assembly of subsystems within the new product dominate the additional costs of disassembly and remanufacturing (Savaskan and Van Wassenhove, 2006).

<sup>2</sup> Hewlett-Packard (HP) Annual Report 2016, <https://www.annualreports.com/Company/hewlett-packard-company>.

<sup>3</sup> Philips Annual Report 2018, <https://www.results.philips.com.cn/publications/ar18?type=annual-report>.



**Assumption 4.** The carbon footprint per unit product  $e$  decreases as collection rates increase. If  $e_n$  and  $e_r$  display the carbon emissions released to produce one unit of new items and carbon reduction due to remanufacturing, then it has the below structure with dual collection channels (Yang et al., 2018a):

$$e(\tau_i + \tau_j) = e_n - (\tau_i + \tau_j)e_r \quad i \neq j = m, e, t$$

**Assumption 5.** The demand is a linear function of retail prices and carbon footprint level. Given the competition on sales in dual-channel models for remanufactured and new products, demands in manufacturer  $D_r^m$  and retailer  $D_n^e$  channels are formulated as follows: In these functions,  $0 < \chi < 1$  presents the degree of consumers' willingness to buy from either online or offline channels. Moreover, the basic market demand is  $a$ , and  $a\mu$  and  $a(1 - \mu)$  represent the number of customers that prefer selling remanufactured and new products from the direct and retail channels, respectively, when the prices are free. We suppose that the effect of carbon the footprint equally affects the demand in offline and online channels.

$$D_n^e = (1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma e(\tau_i + \tau_j)$$

$$D_r^m = \mu a - \lambda_2 p_r^m + \chi(p_n^e - p_r^m) - 0.5\gamma e(\tau_i + \tau_j)$$

Thus, the total market demand is  $D = D_n^e + D_r^m = a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma e(\tau_i + \tau_j)$ . As the demand is nonnegative regardless of the prices, we assume that both  $(1 - \mu)a - 0.5\gamma e_n$  and  $\mu a - 0.5\gamma e_n$  are positive.

**Assumption 6.** The unit transfer price  $b$  that the manufacturer pays to the collector parties (i.e., retailer or the third-party) to motivate them to collect more used products is not higher than the unit cost savings due to remanufacturing (i.e.,  $b < \Delta = c_m - c_r$ )

**Assumption 7.** The manufacturer invests in employing low carbon technologies. It can not only result in carbon reduction, but also increase the demand on both channels. Therefore, a carbon cost function is considered, which is an increasing and convex function of carbon emission reduction level with the following cost structure.  $K$  is the cost coefficient of emission reduction (Yang et al., 2020):

$$C(e) = 0.5K(e_r)^2$$

**Assumption 8.** Normally, the online sales' cost is lower than the offline sales'. Therefore, we assume a fixed cost  $s$  in the profit function of the retailer. (Arshad et al., 2018; He et al., 2016).

**Assumption 9.** The collector pays an average recycling price  $A_i$  for used products, in which  $A_m < \Delta$ , and  $A_e, A_t < b$ . Providing incentives to customers for recycling their EoU products is a commonly adopted strategy by remanufacturers for achieving the economic scale of remanufacturing (Wu, 2015).

### 3.3. Problem formulation

This section explains the mathematical models formulated for each case and provides the optimal policies for each involved party. In all cases, the manufacturer can sell the remanufactured products directly with the price  $p_r^m$  using online channels or the new product via the retailer channel. The retailer can buy the new products with the wholesale price  $w$  from the manufacturer and subsequently sell them to the customer with the price  $p_n^e$  via an offline channel. Therefore, considering Assumption 5, the manufacture earns  $wD_n^e + p_r^m D_r^m$  by selling the products directly to the customers or via the retailer channel.

#### 3.3.1. Dual collection with retailer and manufacturer

Here, both the manufacturer and retailer can collect the used products. The manufacturer incurs costs for manufacturing the new products ( $c_m(1 - \tau_m - \tau_e)D$ ) or remanufacturing the collected used ones ( $c_r(\tau_m + \tau_e)D$ ). Next to the (re)manufacturing costs, there are costs associated with the collection. Here, both the manufacturer and retailer can collect the used products. The manufacturer needs to spend  $A_m \tau_m D$  to collect the used product and  $b\tau_e D$  to motivate the retailer to collect them. Therefore, the manufacturer gross profit can be calculated by

$$\Pi_m^1(p_r^m, w, \tau_m) = wD_n^e + p_r^m D_r^m - c_m(1 - \tau_m - \tau_e)D - c_r(\tau_m + \tau_e)D - b\tau_e D - A_m \tau_m D - C(e) - I_m$$

where  $C(e)$  and  $I_m$  are the cost of carbon emission reduction and investment to collect products, respectively.

Similar to the manufacturer, the retailer earns  $(p_n^e - w)D_n^e$  by selling the products to the customers and  $(b - A_e)\tau_e D$  by collecting the used products from them while spending  $I_e + s$  on the investment and the fixed cost of establishing the offline channel. Thus, the gross profit of the retailer is:

$$\Pi_e^1(p_n^e, \tau_e) = (p_n^e - w)D_n^e + (b - A_e)\tau_e D - I_e - s$$

We considered the Stackelberg game where the manufacturer has enough commitment power to affect the whole market of the products as the leader, while the retailer is the follower. It follows the real-world business, where a giant company has some advantage enabling it to move first. Moreover, this type of game is possible if the leader is the incumbent monopoly of the industry and the follower is a new entrant. Each party wants to decide on the price and the collection rate to maximize the gross profit. To find the optimal policy, the following is assumed:

$$C > \max \left\{ \frac{(1 - \alpha^2)(\lambda_1(b - A_e) - 0.5\gamma e_n)^2}{4(\lambda_1 + \chi)} + (b - A_e)\gamma e_n(1 - \alpha^2), \frac{(1 - \alpha^2)(\lambda_1(b - A_e))^2}{4(\lambda_1 + \chi)}, (b - A_e)[\gamma e_n](1 - \alpha^2) \right\}$$

This assumption assures us that the gross profit function  $\Pi_e^1(p_n^e, \tau_e)$  is a concave function on  $(p_n^e, \tau_e)$ . To find the optimal policy, the manufacturer needs to optimize the profit based on the optimal policy of the retailer. The main mathematical challenge comes from the dependence of  $\tau_e$  on  $\tau_m$ , as  $0 \leq \tau_e \leq 1 - \tau_m$ . In the next theorem, we will tackle this challenge.

**Theorem 1.** Let  $\delta, \theta, \nu, \Gamma_2, h_{11}, h_{12}, h_{13}, h_{22}, h_{23}, h_{33}, R_{p^m}, R_w,$  and  $R_{\tau_m}$  be as defined in Appendix A.1. Let  $H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{12} & h_{22} & h_{23} \\ h_{13} & h_{23} & h_{33} \end{bmatrix}$  be negative definite, and

$$\begin{bmatrix} \bar{p}_r^m \\ \bar{w} \\ \bar{\tau}_m \end{bmatrix} = \frac{1}{\det(H)} \begin{bmatrix} h_{22}h_{33} - h_{23}^2 & -(h_{12}h_{33} - h_{23}h_{13}) & h_{12}h_{23} - h_{22}h_{13} \\ -(h_{12}h_{33} - h_{13}h_{23}) & h_{11}h_{33} - h_{13}^2 & -(h_{11}h_{23} - h_{12}h_{13}) \\ h_{12}h_{23} - h_{13}h_{22} & -(h_{11}h_{23} - h_{13}h_{12}) & h_{11}h_{22} - h_{12}^2 \end{bmatrix} \begin{bmatrix} R_{p^m} \\ R_w \\ R_{\tau_m} \end{bmatrix}.$$

If  $\bar{\tau}_m < 0$ , then in the optimal solution we have  $\tau_m^* = 0$  and

$$\begin{bmatrix} p_r^{m*} \\ w_0^* \end{bmatrix} = \left( \frac{1}{h_{11}h_{22} - h_{12}^2} \begin{bmatrix} h_{22} & -h_{12} \\ -h_{12} & h_{11} \end{bmatrix} \begin{bmatrix} R_{p_r^m} \\ R_w \end{bmatrix} \right).$$

If  $\bar{\tau}_m > 1$ , then in the optimal solution we have  $\tau_m^* = 1$  and

$$\begin{bmatrix} p_r^{m*} \\ w_1^* \end{bmatrix} = \left( \frac{1}{h_{11}h_{22} - h_{12}^2} \begin{bmatrix} h_{22} & -h_{12} \\ -h_{12} & h_{11} \end{bmatrix} \begin{bmatrix} R_{p_r^m} + h_{13} \\ R_w + h_{23} \end{bmatrix} \right).$$

So, let

$$\tilde{\tau}_m = \begin{cases} 0 & \text{if } \bar{\tau}_m < 0 \\ 1 & \text{if } \bar{\tau}_m > 1 \\ \bar{\tau}_m & \text{otherwise} \end{cases}, \quad \tilde{p}_r^m = \begin{cases} p_r^{m*} & \text{if } \bar{\tau}_m < 0 \\ p_r^{m*} & \text{if } \bar{\tau}_m > 1 \\ \bar{p}_r^m & \text{otherwise} \end{cases}, \quad \tilde{w} = \begin{cases} w_0^* & \text{if } \bar{\tau}_m < 0 \\ w_1^* & \text{if } \bar{\tau}_m > 1 \\ \bar{w} & \text{otherwise} \end{cases}$$

$$\tilde{\Gamma}_1 = \frac{(1 - \mu)a + (\lambda_1 + \chi)\tilde{w} + \chi\tilde{p}_r^m + 0.5\gamma(\tilde{\tau}_m e_r - e_n)}{2(\lambda_1 + \chi)}.$$

Also, let  $\bar{\tau}_e = \frac{\tilde{\Gamma}_1 0.5\gamma e_r - 0.5\tilde{w}\gamma e_r + (b - A_e)(a - \lambda_1 \tilde{\Gamma}_1 - \lambda_2 \tilde{p}_r^m - \gamma e_n + e_r \gamma \tilde{\tau}_m)}{\frac{2c}{1 - \alpha^2} - \Gamma_2 0.5\gamma e_r - (b - A_e)[2\gamma e_r - \lambda_1 \Gamma_2]}$

If  $0 \leq \bar{\tau}_e \leq 1 - \tilde{\tau}_m$ , then the optimal solution is

$$p_r^{m*} = \tilde{p}_r^m, \quad w^* = \tilde{w}, \quad \tau_m^* = \tilde{\tau}_m, \quad \tau_e^* = \bar{\tau}_e, \quad p_e^* = \tilde{\Gamma}_1 + \Gamma_2 \bar{\tau}_e.$$

If  $\bar{\tau}_e < 0$ , then we reset  $\nu = \theta = \varphi = \delta = 0$ , and we have the following optimal solutions:

$$p_r^{m*} = \tilde{p}_r^m, \quad w^* = \tilde{w}, \quad \tau_m^* = \tilde{\tau}_m, \quad \tau_e^* = 0, \quad p_e^* = \tilde{\Gamma}_1.$$

If  $\bar{\tau}_e > 1 - \tilde{\tau}_m$ , then we reset  $\nu = -1, \theta = \delta = 0, \varphi = 1$ , and we have the following optimal solution:

$$p_r^{m*} = \tilde{p}_r^m, \quad w^* = \tilde{w}, \quad \tau_m^* = \tilde{\tau}_m, \quad \tau_e^* = 1 - \tilde{\tau}_m, \quad p_e^* = \tilde{\Gamma}_1 + \Gamma_2(1 - \tilde{\tau}_m).$$

**Proof.** Appendix A.2. ■

**Theorem 1** asserts that, based on the values of the initial parameters, the collection of the used products is possibly unprofitable for either party. For instance, if  $\bar{\tau}_e < 0$ , then collecting the used products is unprofitable for the retailer. This is intuitively correct, as the collection depends on the average recycling price for used products paid by the manufacturer to the retailer ( $b$ ) and the average recycling cost of the retailer ( $A_e$ ).

Notably, we assumed  $H$  as negative definite matrix. Although we could not prove this, the numerical experiments showed that the condition on  $C$  is sufficient to satisfy this assumption.

### 3.3.2. Dual collection with manufacturer and third-party

For the second case, we considered a situation where the retailer can only sell the products to customers and cannot collect the used ones. To ensure that the used products are collected efficiently, the manufacturer can hire a third-party to collect used products. Hence, the gross profit of the manufacturer is calculated as follows:

$$\Pi_m^2(p_r^m, w, \tau_m) = wD_n^e + p_r^m D_r^m - c_m(1 - \tau_m - \tau_t)D - c_r(\tau_m + \tau_t)D - b\tau_t D - A_m \tau_m D - C(e) - I_m$$

Here, the retailer's gain is only in selling the products to the customers, with the only cost being establishing the offline channel. Thus, the retailer's gross profit is:

$$\Pi_e^2(p_n^e) = (p_n^e - w)D_n^e - s.$$

For the third-party, the gain is proportional to the amount of collected used products with the only cost being investing in the business. So, the third-party has the profit of:

$$\Pi_t^2(\tau_t) = (b - A_t)\tau_t D - I_t.$$

We considered the Stackelberg game where the manufacturer is the leader who is followed by the retailer. The retailer is also followed by the third-party. At first glance, it may seem that the retailer and third-party can follow the manufacturer in parallel, as only one manages the selling and the other manages the collecting. Notably, based on Assumption 5, demand  $D$  depends not only on the collection rates but also on the product prices, which are set by the manufacturer and retailer. Furthermore, to ensure that we could find the optimal policy of the third-party, we assume that:

$$C > \max \left\{ (1 - \alpha^2)(b - A_t)\gamma e_r, \frac{1 - \alpha^2}{2} ((b - A_t)(a - \gamma(e_n - 3e_r))) \right\}.$$

Similar to the previous case, the dependence of  $\tau_t$  on  $\tau_m$  increases the computational complexity of finding the optimal policies. To tackle this issue, we have the following theorem:

**Theorem 2.** Let  $\Gamma_1, \Gamma_2, \Omega_1, \Omega_2, \Lambda_1, \Lambda_2, h_{11}, h_{12}, h_{13}, h_{22}, h_{23}, h_{33}, \phi, \psi, R_{p_r^m}, R_w,$  and  $R_{\tau_m}$  be as defined in Appendix B.1. Let  $H =$

$\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{12} & h_{22} & h_{23} \\ h_{13} & h_{23} & h_{33} \end{bmatrix}$  be negative definite, and

$$\begin{bmatrix} \bar{p}_r^m \\ \bar{w} \\ \bar{\tau}_m \end{bmatrix} = \frac{-1}{\det(H)} \begin{bmatrix} h_{22}h_{33} - h_{23}^2 & -(h_{12}h_{33} - h_{23}h_{13}) & h_{12}h_{23} - h_{22}h_{13} \\ -(h_{12}h_{33} - h_{13}h_{23}) & h_{11}h_{33} - h_{13}^2 & -(h_{11}h_{23} - h_{12}h_{13}) \\ h_{12}h_{23} - h_{13}h_{22} & -(h_{11}h_{23} - h_{13}h_{12}) & h_{11}h_{22} - h_{12}^2 \end{bmatrix} \begin{bmatrix} R_{p_r^m} \\ R_w \\ R_{\tau_m} \end{bmatrix}.$$

If  $\bar{\tau}_m < 0$ , then in the optimal solution we have  $\tau_m^* = 0$  and

$$\begin{bmatrix} p_r^{m*} \\ w_0^* \end{bmatrix} = \left( \frac{-1}{h_{11}h_{22} - h_{12}^2} \begin{bmatrix} h_{22} & -h_{12} \\ -h_{12} & h_{11} \end{bmatrix} \begin{bmatrix} R_{p_r^m} \\ R_w \end{bmatrix} \right).$$

If  $\bar{\tau}_m > 1$ , then in the optimal solution we have  $\tau_m^* = 1$  and

$$\begin{bmatrix} p_r^{m*} \\ w_1^* \end{bmatrix} = \left( \frac{-1}{h_{11}h_{22} - h_{12}^2} \begin{bmatrix} h_{22} & -h_{12} \\ -h_{12} & h_{11} \end{bmatrix} \begin{bmatrix} R_{p_r^m} + h_{13} \\ R_w + h_{23} \end{bmatrix} \right).$$

Let

$$\tilde{\tau}_m = \begin{cases} 0 & \text{if } \bar{\tau}_m < 0 \\ 1 & \text{if } \bar{\tau}_m > 1 \\ \bar{\tau}_m & \text{otherwise} \end{cases}, \quad \tilde{p}_r^m = \begin{cases} p_r^{m*} & \text{if } \bar{\tau}_m < 0 \\ p_r^{m*} & \text{if } \bar{\tau}_m > 1 \\ \bar{p}_r^m & \text{otherwise} \end{cases}, \quad \tilde{w} = \begin{cases} w_0^* & \text{if } \bar{\tau}_m < 0 \\ w_1^* & \text{if } \bar{\tau}_m > 1 \\ \bar{w} & \text{otherwise} \end{cases},$$

and

$$\tilde{\tau}_t = \frac{(b - A_t)(a - \lambda_1 \tilde{p}_n^e - \lambda_2 \tilde{p}_r^m - \gamma(e_n - \tilde{\tau}_m e_r))}{2(- (b - A_t)\gamma e_r + \frac{c}{1 - \alpha^2})}.$$

If  $\tilde{\tau}_t < 1 - \tilde{\tau}_m$ , then  $(\tilde{\tau}_t, \tilde{p}_n^e, \tilde{\tau}_m, \tilde{p}_r^m, \tilde{w})$  is the optimal solution where

$$\tilde{p}_n^e = \frac{\left( (1 - \mu)a + \chi \tilde{p}_r^m - 0.5\gamma \left( e_n - \left( \tilde{\tau}_m + \frac{(b - A_t)(a - \lambda_2 \tilde{p}_r^m - \gamma(e_n - \tilde{\tau}_m e_r))}{2(- (b - A_t)\gamma e_r + \frac{c}{1 - \alpha^2})} \right) e_r \right) \right)}{2 \left( \lambda_1 + \chi + 0.5\gamma e_r \frac{\lambda_1 (b - A_t)}{2(- (b - A_t)\gamma e_r + \frac{c}{1 - \alpha^2})} \right)} + \frac{\tilde{w}}{2}.$$

Otherwise, we reset  $\Gamma_1 = \frac{\chi}{2(\lambda_1 + \chi)}$ ,  $\Gamma_2 = 0$ ,  $\Omega_1 = \frac{1}{2}$ ,  $\Omega_2 = 0$ ,  $\Lambda_1 = 0$ , and  $\Lambda_2 = -1$  and recalculate the optimal solution  $(1 - \tilde{\tau}_m, \tilde{p}_n^e, \tilde{\tau}_m, \tilde{p}_r^m, \tilde{w})$ , where

$$\tilde{p}_n^e = \frac{((1 - \mu)a + \chi \tilde{p}_r^m - 0.5\gamma(e_n - e_r))}{2(\lambda_1 + \chi)}.$$

**Proof.** Appendix B.2. ■

The second part of Theorem 2, where the third-party collects what remains in the market, may be seen as more intuitive than the first part as the third-party earns more if it collects more. However, we emphasize that the third-party's investment in the business is also a function of the collection rate and has a great impact. If the investment is independent of the collection rate, then the optimal policy is indeed  $(1 - \tilde{\tau}_m, \tilde{p}_n^e, \tilde{\tau}_m, \tilde{p}_r^m, \tilde{w})$ .

Similar to the previous case, we could not prove that the matrix  $H$  is negative definite for the considered value of  $C$ , though our numerical results suggest that this condition holds.

### 3.3.3. Dual collection with retailer and third-party

In the third case, the manufacturer is only responsible for selling the products, while the retailer and the third-party have the responsibility of collecting the used products. Therefore, the manufacturer has a gross profit of:

$$\Pi_m^3(p_r^m, w, \tau_m) = wD_n^e + p_r^m D_r^m - c_m(1 - \tau_e - \tau_t)D - c_r(\tau_e + \tau_t)D - b(\tau_e + \tau_t)D - C(e),$$

The retailer has a gross profit of:

$$\Pi_e^3(p_n^e, \tau_e) = (p_n^e - w)D_n^e + (b - A_e)\tau_e D - I_e - s$$

And the third-party has a gross profit of:

$$\Pi_t^3(\tau_t) = (b - A_t)\tau_t D - I_t.$$

Similar to the second case, we considered the Stackelberg game where the third-party follows the retailer who follows the manufacturer. To ensure that the third-party and the retailer have concave gross profits, we assume that

$$C > \frac{((0.5\gamma(1 + \delta_2)e_r) + (b - A_e)(-\lambda_1 + \gamma\delta_1 e_r))(1 - \alpha^2)}{2\alpha\delta_1\delta_2},$$

**Table 2**  
Parameter settings in the numerical study

Parameters	$c_m$	$c_r$	$s$	$a$	$\mu$	$\lambda_1$	$\lambda_2$	$e_n$	$e_r$	$K$	$A_m$	$A_e$	$A_t$	$b$	$C$
Values	20	10	3	100	0.30	0.35	0.25	9.5	6.5	0.5	10	8.5	5	9	1000

and

$$C > \max \left\{ \frac{-C_1 \pm \sqrt{C_1^2 - 4C_0C_2}}{2C_2}, (1 - \alpha^2)(b - A_t)\gamma e_r, \frac{2(b - A_e)(\gamma(1 + \delta_2)e_r)(1 - \alpha^2)}{(2 + 2\alpha\delta_2^2)} \right\},$$

where the definitions of  $C_0$ ,  $C_1$ , and  $C_2$  can be found in Appendix C.1. In the next theorem, we show what the optimal policies are for the manufacturer, retailer, and third-party.

**Theorem 3.** Let  $\delta_1, \delta_2, h_{11}^e, h_{12}^e, h_{22}^e, \Gamma_0, \Gamma_1, \Gamma_2, \Gamma_3, \Omega_1, \Omega_2, \Omega_3, \Lambda_0, \Lambda_1, \Lambda_2, \Lambda_3, R_1^m, R_2^m, h_{11}^m, h_{12}^m$ , and  $h_{22}^m$  be as defined in Appendix C.1. Let us assume that  $H^m = \begin{bmatrix} h_{11}^m & h_{12}^m \\ h_{12}^m & h_{22}^m \end{bmatrix}$  is a negative definite matrix. We set

$$\begin{bmatrix} \bar{p}_r^m \\ \bar{w} \end{bmatrix} = -\frac{1}{h_{11}^m h_{22}^m - h_{12}^m{}^2} \begin{bmatrix} h_{22}^m & -h_{12}^m \\ -h_{12}^m & h_{11}^m \end{bmatrix} \begin{bmatrix} R_1^m \\ R_2^m \end{bmatrix}.$$

Moreover, we let

$$\theta^e = \frac{(b - A_t)(a - \lambda_2 \bar{p}_r^m - \gamma e_n)}{-2(b - A_t)\gamma e_r + C \frac{2}{1 - \alpha^2}}$$

$$R_1^e = ((1 - \mu)a + \chi \bar{p}_r^m - 0.5\gamma(e_n - \theta^e e_r)) - \bar{w}(-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r) - C \frac{(2\alpha\delta_1\theta^e)}{1 - \alpha^2},$$

$$R_2^e = -\bar{w}(0.5\gamma(1 + \delta_2)e_r) + (b - A_e)(a - \lambda_2 \bar{p}_r^m - \gamma(e_n - \theta^e e_r)) - C \frac{(2\alpha\delta_2\theta^e)}{1 - \alpha^2},$$

$$h_{11}^e = 2(-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r) - C \frac{(2\alpha\delta_1^2)}{1 - \alpha^2},$$

$$h_{12}^e = (0.5\gamma(1 + \delta_2)e_r) + (b - A_e)(-\lambda_1 + \gamma\delta_1 e_r) - C \frac{(2\alpha\delta_1\delta_2)}{1 - \alpha^2},$$

$$h_{22}^e = 2(b - A_e)(\gamma(1 + \delta_2)e_r) - C \frac{(2 + 2\alpha\delta_2^2)}{1 - \alpha^2},$$

$$\begin{bmatrix} \bar{p}_n^e \\ \bar{\tau}_e \end{bmatrix} = -\frac{1}{C_2C^2 + C_1C + C_0} \begin{bmatrix} h_{22}^e & -h_{12}^e \\ -h_{12}^e & h_{11}^e \end{bmatrix} \begin{bmatrix} R_1^e \\ R_2^e \end{bmatrix},$$

$$\bar{\tau}_t = \frac{(b - A_t)(a - \lambda_1 \bar{p}_n^e - \lambda_2 \bar{p}_r^m - \gamma(e_n - \bar{\tau}_e e_r))}{-2(b - A_t)\gamma e_r + C \frac{2}{1 - \alpha^2}}.$$

If  $\bar{\tau}_e < 1$  and  $\bar{\tau}_t < 1 - \bar{\tau}_e$ , then optimal solution is  $(\bar{\tau}_t, \bar{\tau}_e, \bar{p}_n^e, \bar{p}_r^m, \bar{w}) = (\bar{\tau}_t, \bar{\tau}_e, \bar{p}_n^e, \bar{p}_r^m, \bar{w})$ . Otherwise, the solution  $(\bar{\tau}_t, \bar{\tau}_e, \bar{p}_n^e, \bar{p}_r^m, \bar{w})$  is among the following points  $\mathcal{A}$  and  $\mathcal{B}$ :

$\mathcal{A}$ :  $(1 - \bar{\tau}_e, \bar{\tau}_e, \bar{p}_n^e, \bar{p}_r^m, \bar{w})$  where the values are calculated by re-setting  $\delta_1 = \Gamma_0 = 0, \delta_2 = -1, \theta^e = \Lambda_0 = \Lambda_3 = 1, \Gamma_3 = -\Gamma_2$ , and  $\Omega_3 = -\Omega_2$ .

$\mathcal{B}$ :  $(0, 1, \frac{-R_1^e - h_{12}^e}{h_{11}^e}, \bar{p}_r^m, \bar{w})$  where the values are calculated by re-setting,  $\delta_1, \delta_2, \theta^e, \Gamma_0, \Lambda_0, \Gamma_2, \Gamma_3, \Omega_2, \Omega_3$ , and  $\Lambda_3$  to 0,  $\Gamma_1 = \frac{-\chi}{h_{11}^e}, \Omega_1 = \frac{(-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r)}{h_{11}^e}, \Lambda_1 = \frac{-((1 - \mu)a - 0.5\gamma e_n) - h_{12}^e}{h_{11}^e}$ , and  $\Lambda_2 = 1$ .

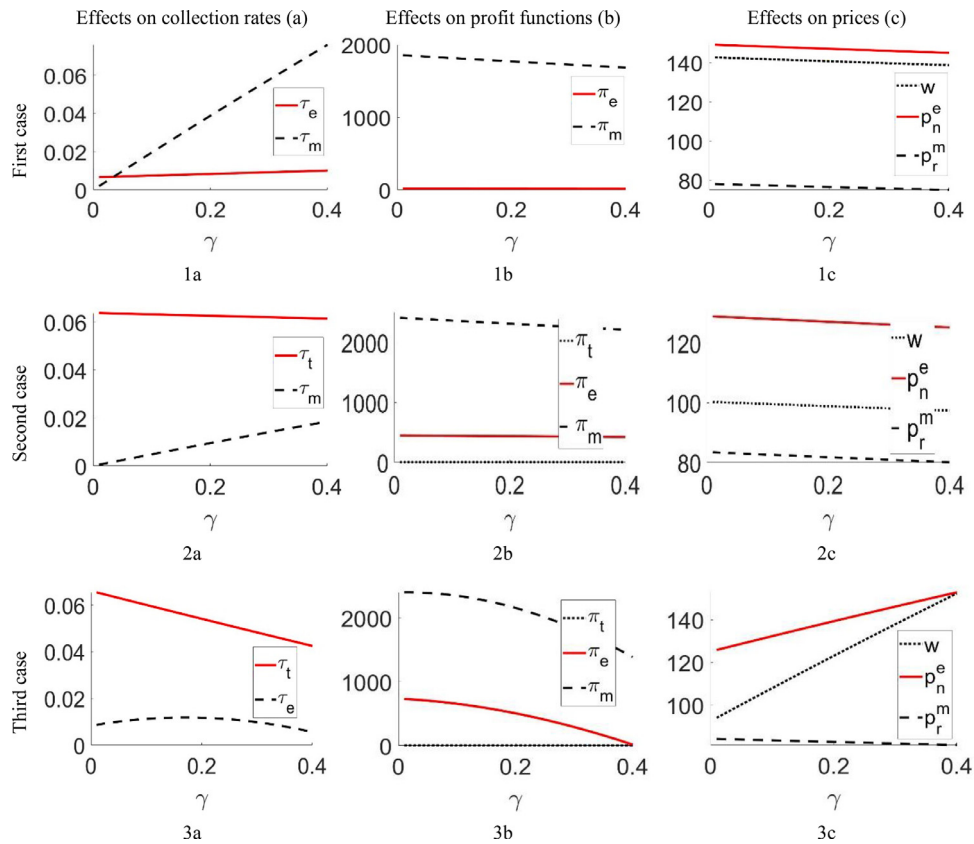
**Proof.** Appendix C.2 ■

In the next section, we analyze the behavior of the optimal policies for each case when  $\alpha, \gamma$ , and  $\chi$  change.

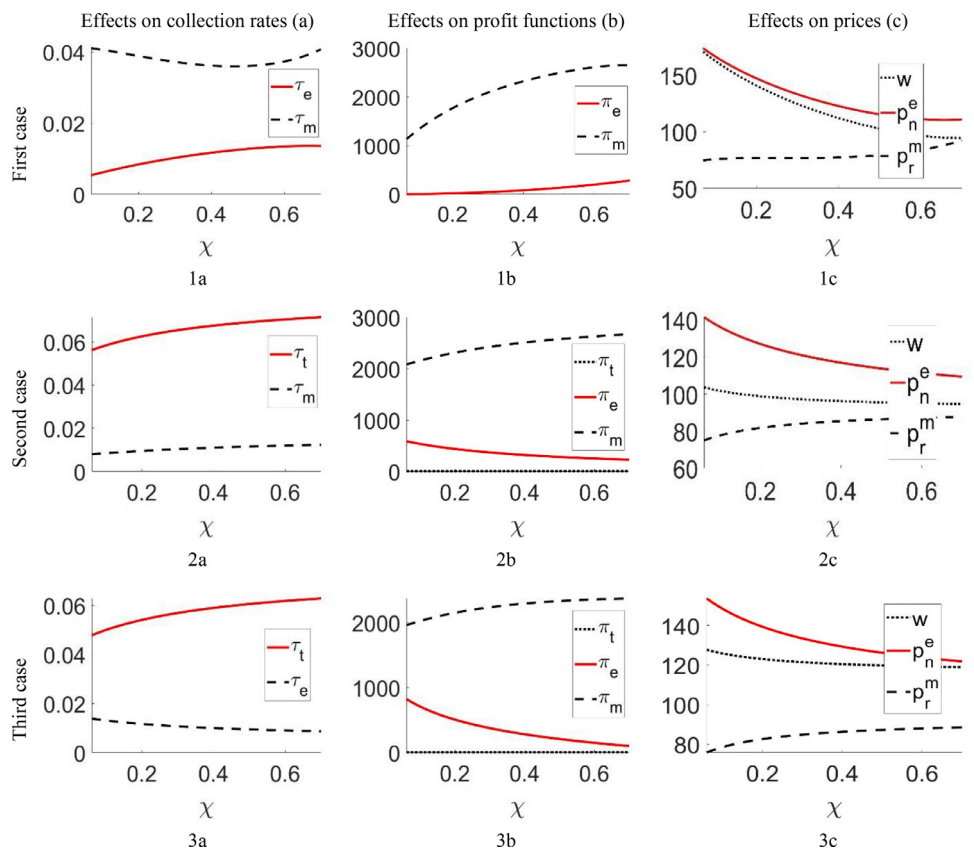
#### 4. Results

In this section, we numerically analyze the sensitivity of the optimal decisions and profits of the players under different scenarios and investigate the interaction of consumer preference and the developed models. The parameters are assumed as shown in Table 2. Figures 3, 4, and 5 present the sensitivity of the decision variables and profit functions to the alteration of important parameters  $\gamma, \chi$ , and  $\alpha$  (i.e., consumer’s sensitivity to the carbon footprint, customers’ willingness to choose the remanufactured product, and competing coefficient between the two collection channels) for three developed cases, respectively.





**Fig. 3.** Analyzing the effect of consumer's sensitivity to the carbon footprint ( $\gamma$ ) on decision variables and profit functions in three developed cases: a. collection rate by the collector party; b. profit function of the involved parties; c. the wholesale price of the new product and price of the new and remanufactured product.



**Fig. 4.** Analyzing the effect of customers' willingness to choose the remanufactured product ( $\chi$ ) on decision variables and profit functions in three developed cases: a. collection rate by the collector party; b. profit function of the involved parties; c. wholesale price of the new product and price of the new and remanufactured product.

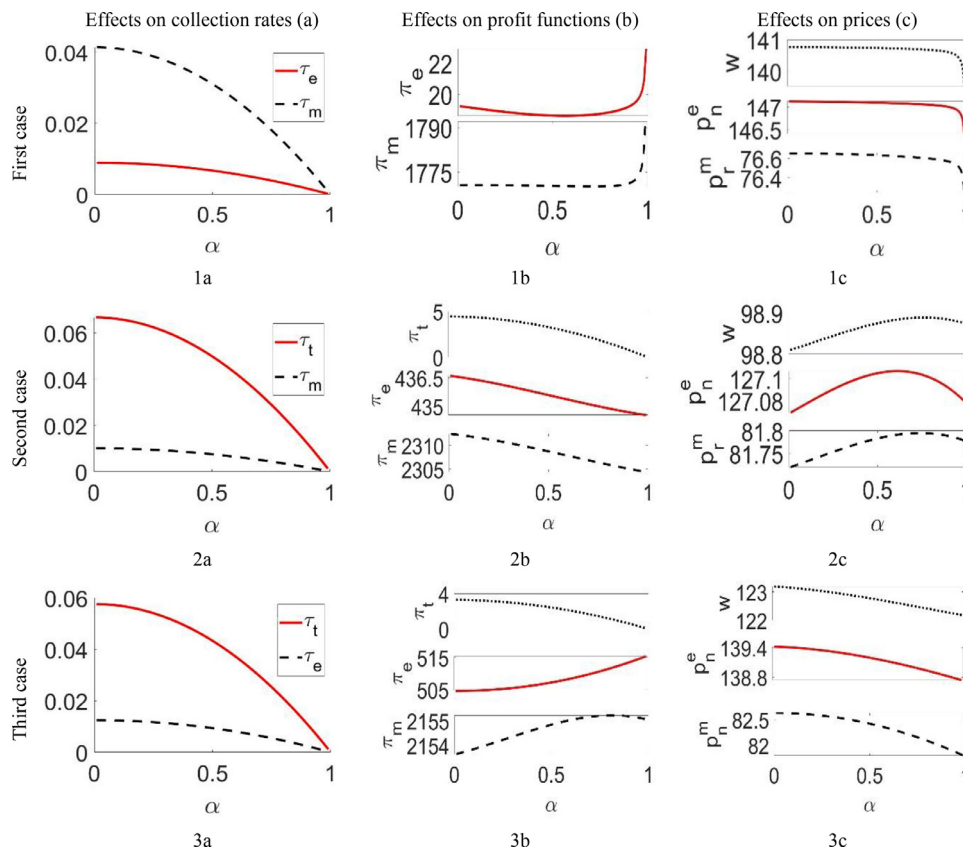


Fig. 5. Analyzing the effect of competing coefficient between the two collection channels ( $\alpha$ ) on decision variables and profit functions in three developed cases: a. collection rate by the collector party; b. profit function of the involved parties; c. the wholesale price of the new product and price of the new and remanufactured product.

4.1. Analyzing the impact of changes in consumer's sensitivity to the carbon footprint

This subsection analyzes the impacts of changes in consumers' behavior regarding the carbon footprint in the three models. As the column (a) in Fig. 3 shows,  $\gamma$  has a considerable positive effect on the manufacturer's collection rate and some positive effects on the retailer's collection rate in the first case (1a). However, in the second case (2a), when the retailer is replaced by the third-party as the collector, the manufacturer's collection rate sensitivity decreases. In this regard, in the retailer's presence as the collector (3a), the reaction of the third-party increases when the consumer's sensitivity to the carbon footprint changes and the third-party prefers to collect less.

Regarding the effect of  $\gamma$  on profits, if  $\gamma$  increases, the manufacturer's profit decreases, while it does not considerably affect the retailer's profit in the first case (1b). The same applies to the second case (2b); furthermore, it does not affect the third-party's profit. In the third case (3b), the increase in  $\gamma$  has a negative effect on the manufacturer's and retailer's profits, but it does not affect the third-party's profit. The rate of profit changes is severe when the retailer and third-party compete on collection compared to the first and second cases (1b and 2b).

In Fig. 3, column (c), the effects of  $\gamma$  on the prices are studied. In the first case (1c),  $\gamma$  has a small negative effect on the manufacturer's wholesale price of the new product to the retailer  $w$ , the price of the new product through the retailer channel  $p_n^e$ , and the price of remanufactured product through the manufacturer channel  $p_r^m$ . The same applies to the second case (2c). In the third case, however,  $\gamma$  affects both  $w$  and  $p_n^e$  positively and  $p_r^m$  negatively. In Fig. 3c, when gamma increases, demand for remanufactured products increases, and demand for new products decreases. The decrease in the demand for the new product is such that it affects the total demand and makes it decrease.

4.2. Analyzing the impact of changes in consumer's willingness to choose remanufactured items

This subsection analyzes the impacts of changes in consumers' behavior regarding remanufactured products in the three models. Fig. 4 shows that in the first case, an increase in  $\chi$  has first a negative and then a positive effect on the manufacturer's collection rate and a decreasing positive effect on the retailer's collection rate. In the second case,  $\chi$  has a decreasing positive impact on both the manufacturer's and third-party's collection rate. In the third case,  $\chi$  has a decreasing positive effect on the third-party's collection rate and a decreasing negative effect on the retailer's collection rate.

Regarding the effects on profit,  $\chi$  has a decreasing positive effect on the manufacturer's profits and an increasingly positive effect on the retailer's profit in the first case (Fig. 4. 1b). In the second case (Fig. 4. 2b),  $\chi$  has a decreasing positive effect on the manufacturer's profits and a decreasing negative effect on the retailer's profits. In the third case,  $\chi$  has a decreasing positive effect on the manufacturer's profits and a decreasing negative effect on the retailer's profits. However,  $\chi$  does not significantly affect the third-party's profits in these cases.

Considering the change in prices, in all cases,  $\chi$  has a decreasing negative effect on the manufacturer's wholesale price of the new product and the price of the new product through the retailer channel. However, it has an increasingly positive effect on the remanufactured product's price through the manufacturer channel ( $p_r^m$ ). Prices are decreasing more steeply in the first case (Fig. 4. 1c).

#### 4.3. Analyzing the impact of collectors' competition

The effects of competition are shown in Fig. 5. It shows that the more the competition increases, the more the collectors' preferences for collection decrease. Similar results have been seen in the literature (Liu et al., 2017). Furthermore, the manufacturer and retailer show similar actions for collection when competing with the third-party. The manufacturer's collection strategy is more stable when competing with the third-party compared to the first case in which the retailer is the competitor.

Regarding the effect of  $\alpha$  on profit, in the first case (Fig. 5. 1b), the players' profit only drastically increases when the competition is very high. The profit change pattern was similar for all the involved parties in the second case (Fig. 5. 2b). The change in the profit function is different for each party in the third case (Fig. 5. 3b) such that it is convex for the manufacturer. However, contrary to the third-party, the retailer's profit increases when  $\alpha$  increases.

Fig. 5. 1c and 3c show that the competition has a negative effect on prices (i.e., wholesale and retail prices of new products and price of remanufactured products), and they continuously decrease. However, in the second case, these prices first increase and then decrease as competition increases (Fig. 5. 1b).

## 5. Discussion

### 5.1. Internal and single-parameter comparisons

Overall, when consumers become more sensitive to the carbon footprint, the manufacturer prefers to collect more used products than other parties and consumers' behavior in this context impressed the manufacturer more. Consumers' sensitivity to carbon footprint has a negative effect or at least no effect on the profit functions of involved parties. Regarding profit, the second case (the manufacturer and the third-party collect) is the best from the manufacturer's perspective when consumers become sensitive to the carbon footprint. Additionally, the price difference between retail and wholesale prices is interesting for the retailer in the second case.

Generally, the effect of customers' willingness to choose the remanufactured product on the collection rate of both the manufacturer and third-party is similar. However, in these situations, the retailer's preference to collect the core decreases in the third-party's presence. The gap between wholesale price and new product price decreases as consumers' preference to choose remanufactured products increases in the presence of the third-party as one of the collectors. In this case, the first case (the manufacturer and the retailer collect) is especially interesting for the retailer.

When competition occurs on the collection, the reaction of the retailer and third-party is similar. However, the manufacturer's collection reaction depends on the competitor. If competition on collection increases, considering the profit, the best scenario for both the retailer and manufacturer is the third case. When there is increasing competition, the third case is the best for consumers where competition exists between the third-party and retailer in collecting the core.

### 5.2. External and dual-parameter comparisons

When there is core collection competition, customers' willingness to choose the remanufactured product increases the manufacturer's profit. However, this situation is reversed when consumers' sensitivity to carbon footprints increases (see columns (a) and (b) in Fig. 6). If consumers' sensitivity to both carbon footprint and choosing remanufacturing products increases, the first case (Fig. 6. 1c) is better for the manufacturer regarding the effect on profit. Overall, considering all the effects on the profit function, the first case is the best for the manufacturer. Therefore, third-party entry is not in the manufacturer's interest.

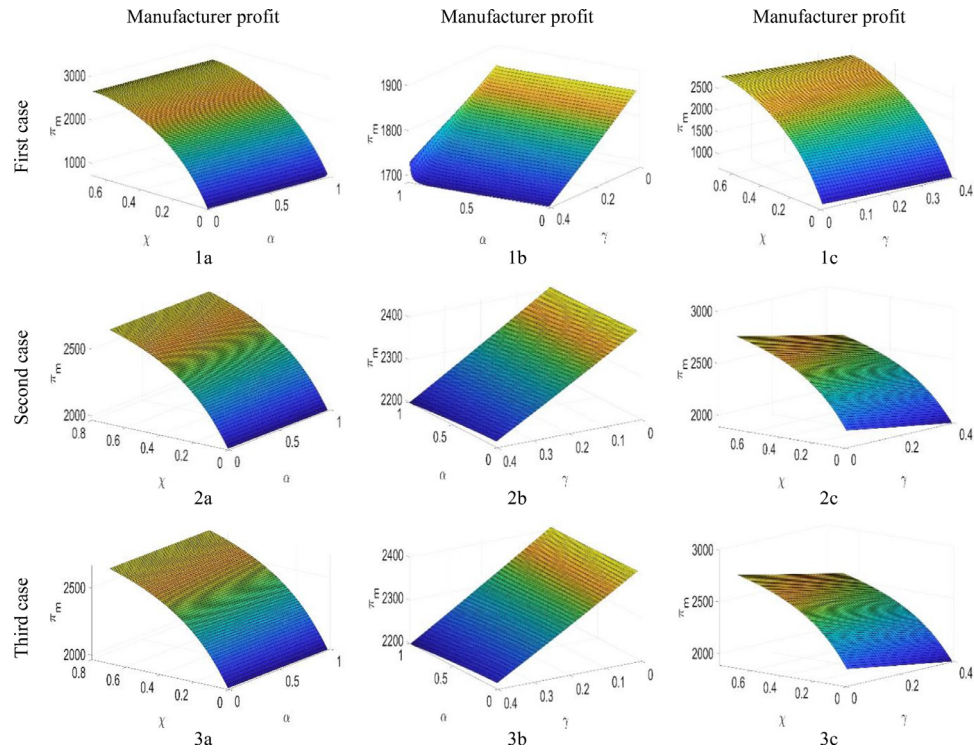
If the competition for collecting the core and consumers' willingness to choose remanufactured products increase simultaneously, the first case is better for the retailer to make a profit (Fig. 7. 1a). If the consumer's sensitivity to the carbon footprint and competition for collecting the cores decreases simultaneously, the profit of the retailer generally increases. When consumers' sensitivity increases to both choosing the remanufactured products and carbon footprint simultaneously, the first case is preferred by the retailer regarding the profit. The most influential factor in the retailer's profit is customers' willingness to choose the remanufactured product.

The simultaneous increase in the collection competition and customers' willingness to choose the remanufactured product positively impacts the third-party's profit in the second and third cases. However, it changed to a negative impact when both parameters increased simultaneously (Fig. 8. 1a–2a). When there is no competition for collection, third-party can obtain the maximum profit by growing in consumers' sensitivity to choose the remanufactured products. Considering third-party's profit, Fig. 8. 1b–2b illustrate that the influence of competition on the core's collection exceeds consumers' sensitivity to the carbon footprint. Overall,  $\chi$  is the most important parameter for the third-party, and it is dependent on the consumers' behavior. There is no preferred case for the third-party.

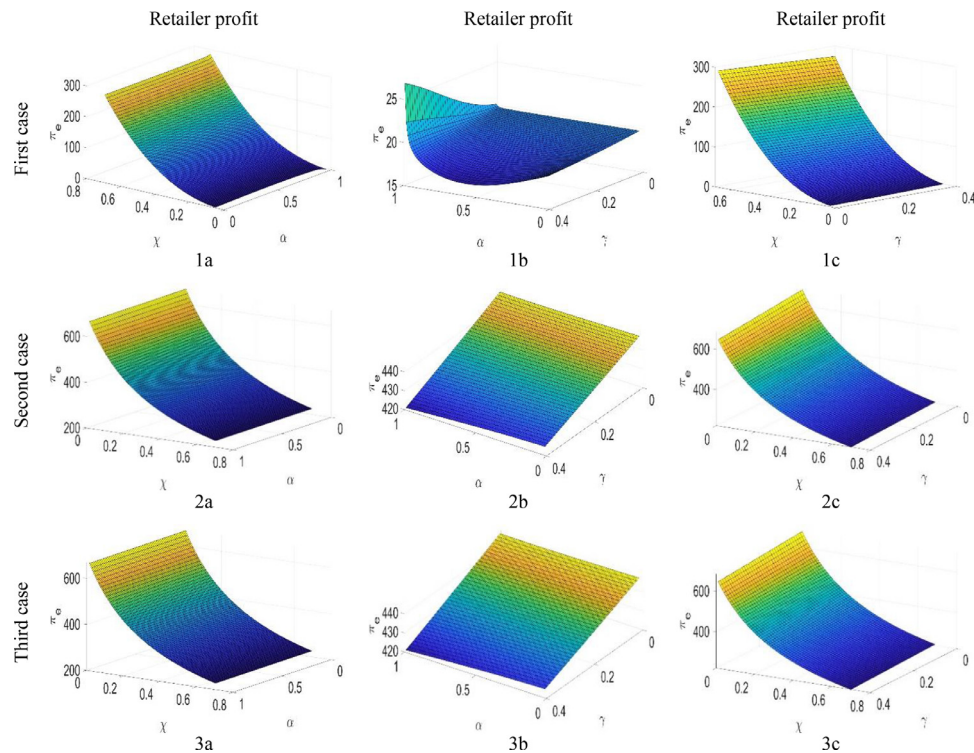
The interesting finding is that the involved parties are mostly affected by the consumers' behavior regarding their willingness to choose the remanufactured products and sensitivity to the carbon footprint; meanwhile, the first one is a more influential factor.

### 5.3. Managerial insight

Managers need to consider different models and test different scenarios to find optimal solutions and operation models for their businesses. However, considering the complexities and dynamics of markets, consumer behavior, and competitors' actions, it should also be understood that even carefully built models may not fully correspond to the market reality. Meanwhile, based on the responses to the research questions formulated in the introduction section, we can suggest some helpful guidelines to establish appropriate strategies.

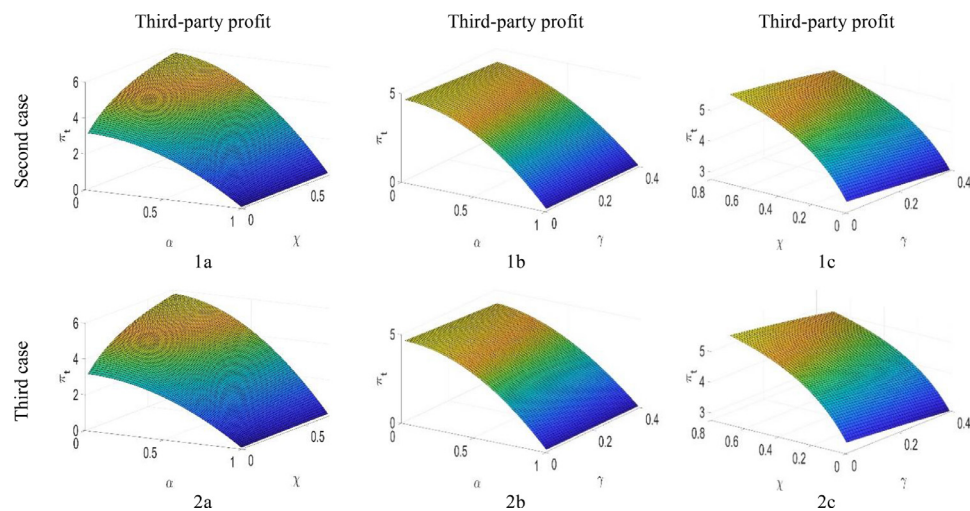


**Fig. 6.** Analyzing the simultaneous effects of essential parameters on the manufacturer's profit function in three developed cases: a. simultaneous effects of customers' willingness to choose the remanufactured product ( $\chi$ ) and competing coefficient between the two collection channels ( $\alpha$ ); b. simultaneous effects of consumer's sensitivity to the carbon footprint ( $\gamma$ ) and competing coefficient between the two collection channels ( $\alpha$ ); and c. simultaneous effects of customers' willingness to choose the remanufactured product ( $\chi$ ) and consumer's sensitivity to the carbon footprint ( $\gamma$ ).



**Fig. 7.** Analyzing the simultaneous effects of essential parameters on the retailer's profit function in three developed cases: a. simultaneous effects of customers' willingness to choose the remanufactured product ( $\chi$ ) and competing coefficient between the two collection channels ( $\alpha$ ); b. simultaneous effects of consumer's sensitivity to the carbon footprint ( $\gamma$ ) and competing coefficient between the two collection channels ( $\alpha$ ); and c. simultaneous effects of customers' willingness to choose the remanufactured product ( $\chi$ ) and consumer's sensitivity to the carbon footprint ( $\gamma$ ).





**Fig. 8.** Analyzing the simultaneous effects of essential parameters on the third-party's profit function in three developed cases: a. simultaneous effects of customers' willingness to choose the remanufactured product ( $\chi$ ) and competing coefficient between the two collection channels ( $\alpha$ ); b. simultaneous effects of consumer's sensitivity to the carbon footprint ( $\gamma$ ) and competing coefficient between the two collection channels ( $\alpha$ ); and c. simultaneous effects of customers' willingness to choose the remanufactured product ( $\chi$ ) and consumer's sensitivity to the carbon footprint ( $\gamma$ ).

Overall, consumer sensitivity to carbon footprint can have more impact on the involved parties' collection effort compared to change caused by the willingness to choose the remanufactured product; thus, the manufacturer is more affected. Interestingly, the more consumers desire to select the remanufactured products, the more differences exist between the collection rates of the collector parties. Thus, this consumer behavior induces divergent collection decisions (see the increasing gaps between the lines in Fig. 4. column (a)).

We found that sustainable consumers are the winners of new products' market due to the decreasing trend of the retail (wholesale) price of these products in all cases. There was only one exception (see Fig. 3. 3c). Compared to the similar single-collection CLSC models (Xu and Wang, 2018), we can see that the suggested dual-collection CLSC models have advantages for consumers. This reduction logically increases when consumers prefer to buy remanufactured products.

Our results show that, overall, competition on collection is not a sustainable strategy, as it decreases the collection effort in all cases. It follows the findings of the previous study (Huang et al., 2013). When the retailer and third-party compete (third case), this decreasing effect continues even further. Although this case sounds interesting for the consumer because of price reduction, it can be limited by the social planners (government) if they want to give priority to the environment by establishing appropriate laws. This discloses the situation in which economic strategy contrasts environmental strategy. In a competition situation, the second case is the worst because of the lower collection rate, less profit of the players, and increasing prices for consumers.

Considering the profit, the manufacturer is more robust against the competition, and it is expected as she is the leader of the market. If the manufacturer wants to produce in a stable market, the first case is the best. In other cases, she can use remanufacturing as a competitive advantage and earn more profit. In the retailer's case, the most influential factor on the payoff is the willingness to choose the remanufactured product, and accordingly, the first case works best. The third-party's profit in all cases is almost similar. Therefore, there is no priority for the third party, and intense competition may worsen the third-party situation.

## 6. Conclusion

Studying CLSCs through game theory has contributed to the literature, as it provides an opportunity to investigate the optimal decisions of the entities analytically. This study analyzed three CLSC models under the manufacturer as the Stackelberg game leader with different collection structures when consumers are sensitive to the produced carbon footprint and have different preferences to choose remanufactured products. The first model was based on the collection competition between manufacturer and retailer. In the second and third models, one of these parties was replaced with the third-party to explore the differences. We found the optimum collection rates, price of new and remanufactured products, and wholesale prices of new products in each scenario. Furthermore, we illustrated the dual effects of change in important parameters (i.e., competition coefficient, consumers' willingness to choose the remanufactured product, and their sensitivity to carbon footprint) simultaneously on each party's profit in each case. Considering all the impacts, the first case was best for the manufacturer. Different strategies were discussed based on the results.

The significant contribution of this study can be extended in the following aspects: The formulated demand function, which has a new format, can be extended to an uncertain situation by considering the stochastic parameters. Different types of contracts, such as revenue sharing, can be included. Finally, the impact of the reward-penalty mechanism, especially by the government, will be an interesting topic in the presence of customers who are environmentally aware through sensitivity to the carbon footprint.

## Declaration of Competing interest

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

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**Appendixes**

*A.1. Definition of notations*

Let us set

$$\Gamma_2 = \frac{[\lambda_1(A_e - b) + 0.5\gamma e_r]}{2(\lambda_1 + \chi)} \quad \delta = \frac{-0.5\gamma e_r - (b - A_e)(\lambda_1)}{\frac{4C}{1-\alpha^2} - \Gamma_2\gamma e_r - 2(b - A_e)(2\gamma e_r - \lambda_1\Gamma_2)}$$

$$v = \frac{0.5\gamma e_r\gamma e_r + 2(b - A_e)(-\lambda_1 0.5\gamma e_r + \gamma e_r)}{\frac{4C}{1-\alpha^2} - \Gamma_2\gamma e_r - 2(b - A_e)(2\gamma e_r - \lambda_1\Gamma_2)}$$

$$\theta = \frac{\frac{\chi}{2(\lambda_1 + \chi)}\gamma e_r + 2(b - A_e)(-\lambda_1 \frac{\chi}{2(\lambda_1 + \chi)} - \lambda_2)}{\frac{4C}{1-\alpha^2} - \Gamma_2\gamma e_r - 2(b - A_e)(2\gamma e_r - \lambda_1\Gamma_2)}$$

Also, let

$$h_{11} = 2\left(\frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2\theta\right)(\chi + \lambda_1[-c_m + c_r + b]\theta) + 2\lambda_2([-c_m + c_r + b]\theta - 1) - 2\chi - 2\gamma\theta^2 e_r[-c_m + c_r + b] - \frac{2\alpha C\theta^2}{1 - \alpha^2},$$

$$h_{12} = [-(\lambda_1 + \chi)\left(\frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2\theta\right) + \chi + 0.5\theta e_r] + [\chi(0.5 + \Gamma_2\delta) - 0.5\gamma(-\delta)e_r] \\ - [-\lambda_1\left(\frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2\theta\right) - \lambda_2 + \gamma(\theta e_r)][c_m(-\delta) + c_r(\delta) + b\delta] \\ - [\lambda_1(0.5 + \Gamma_2\delta) - \gamma(-\delta)e_r][c_m(\theta) + c_r(\theta) + b\theta] - \frac{2\alpha C\theta\delta}{1 - \alpha^2},$$

$$h_{13} = \gamma(1 + v)e_r[0.5 - \theta[-c_m + c_r + b]] + (0.5\gamma e_r + \Gamma_2v)[\chi + \lambda_1\theta[-c_m + c_r + b]] \\ - [-\lambda_1\left(\frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2\theta\right) - \lambda_2 + \gamma(\theta e_r)][c_m(-1 - v) + c_r(1 + v) + bv + A_m] \\ - \frac{2\alpha C\theta v}{1 - \alpha^2},$$

$$h_{22} = 2[-(\lambda_1 + \chi)(0.5 + \Gamma_2\delta) + 0.5\gamma\delta e_r] + 2[\lambda_1(0.5 + \Gamma_2\delta) - \gamma\delta e_r][-c_m + c_r + b]\delta - \frac{2\alpha C\delta^2}{1 - \alpha^2},$$

$$h_{23} = [\lambda_1(0.5 + \Gamma_2\delta) - \gamma\delta e_r][c_m(-1 - v) + c_r(1 + v) + bv + A_m] \\ + (0.5\gamma e_r + \Gamma_2v)[-(\lambda_1 + \chi) + \lambda_1\delta(-c_m + c_r + b)] \\ + \gamma(1 + v)e_r[0.5 - \delta(-c_m + c_r + b)] - \frac{2\alpha C\delta v}{1 - \alpha^2},$$

$$h_{33} = -2[-\lambda_1(0.5\gamma e_r + \Gamma_2v) + \gamma(1 + v)e_r][c_m(-1 - v) + c_r(1 + v) + bv + A_m] - \frac{2C + 2\alpha C v^2}{1 - \alpha^2},$$

$$\varphi = \frac{(1 - \mu)a - 0.5\gamma e_n}{2(\lambda_1 + \chi)}, \quad \psi = \frac{\varphi\gamma e_r + 2(b - A_e)(a - \lambda_1\varphi - \gamma e_n)}{\frac{4C}{1-\alpha^2} - \Gamma_2\gamma e_r - 2(b - A_e)(2\gamma e_r - \lambda_1\Gamma_2)},$$

$$R_{p_r^m} = [\mu a + \chi(\varphi + \Gamma_2\psi) - 0.5\gamma(e_n - (\psi)e_r)] \\ - [-\lambda_1\left(\frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2\theta\right) - \lambda_2 + \gamma(\theta e_r)][c_m(1 - \psi) + c_r(\psi) + b\psi] \\ - [a - \lambda_1(\varphi + \Gamma_2\psi) - \gamma(e_n - (\psi)e_r)][c_m(\theta) + c_r(\theta) + b\theta],$$

$$R_w = [(1 - \mu)a - \lambda_1(\varphi + \Gamma_2\psi) - \chi((\varphi + \Gamma_2\psi)) - 0.5\gamma(e_n - (\psi)e_r)] \\ - [-\lambda_1(0.5 + \Gamma_2\delta) - \gamma(-\delta)e_r][c_m(1 - \psi) + c_r(\psi) + b\psi] \\ - [a - \lambda_1(\varphi + \Gamma_2\psi) - \gamma(e_n - (\psi)e_r)][c_m(-\delta) + c_r(\delta) + b\delta],$$

$$R_{\tau_m} = [-\lambda_1(0.5\gamma e_r + \Gamma_2v) - \gamma(-(1 + v)e_r)][c_m(1 - \psi) + c_r(\psi) + b\psi] \\ - [a - \lambda_1(\varphi + \Gamma_2\psi) - \gamma(e_n - (\psi)e_r)][c_m(-1 - v) + c_r(1 + v) + bv + A_m] \\ - \frac{2\alpha C v \psi}{1 - \alpha^2}.$$

*A.2. Proof of Theorem 1.*

We can rewrite the total net profit of manufacturer as follows:

$$\Pi_m^1(p_r^m, w, \tau_m, e_r, b) \\ = w[(1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma[e_n - (\tau_m + \tau_e)e_r]] \\ + p_r^m[\mu a - \lambda_2 p_r^m + \chi(p_n^e - p_r^m) - 0.5\gamma[e_n - (\tau_m + \tau_e)e_r]] \\ - [a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma e(\tau_m + \tau_e)][c_m(1 - \tau_m - \tau_e) + c_r(\tau_m + \tau_e) + b\tau_e + A_m \tau_m] \\ - \frac{C\tau_m^2 + \alpha C\tau_e^2}{1 - \alpha^2} - 0.5K(e_r)^2$$

Moreover, the retailer net profit can be rewritten as

$$\Pi_e^1(p_n^e, \tau_e) = (p_n^e - w)[(1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma(e_n - (\tau_e)e_r)] + (b - A_e)\tau_e[a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tau_e + \tau_m)e_r)] - \frac{C\tau_e^2 + \alpha C\tau_m^2}{1 - \alpha^2} - s.$$

We first show that  $\Pi_e^1(p_n^e, \tau_e)$  is concave. We know that the first partial derivate is

$$\frac{\partial \Pi_e^1(p_n^e, \tau_e)}{\partial p_n^e} = [(1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma(e_n - (\tau_e + \tau_m)e_r)] + (p_n^e - w)[- \lambda_1 - \chi] + (b - A_e)\tau_e[- \lambda_1],$$

$$\frac{\partial \Pi_e^1(p_n^e, \tau_e)}{\partial \tau_e} = (p_n^e - w)[0.5\gamma e_r] + (b - A_e)[a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tau_e + \tau_m)e_r)] + (b - A_e)\tau_e[\gamma e_r] - \frac{2C\tau_e}{1 - \alpha^2}.$$

Hence, we have

$$\frac{\partial^2 \Pi_e^1(p_n^e, \tau_e)}{\partial p_n^e{}^2} = -2(\lambda_1 + \chi), \quad \frac{\partial \Pi_e^1(p_n^e, \tau_e)}{\partial p_n^e \partial \tau_e} = [0.5\gamma e_r] - (b - A_e)[\lambda_1],$$

$$\frac{\partial^2 \Pi_e^1(p_n^e, \tau_e)}{\partial \tau_e^2} = (b - A_e)[\gamma e_r] + (b - A_e)[\gamma e_r] - \frac{2C}{1 - \alpha^2} = 2\gamma e_r(b - A_e) - \frac{2C}{1 - \alpha^2},$$

Clearly, we have  $\frac{\partial^2 \Pi_e^1(p_n^e, \tau_e)}{\partial p_n^e{}^2} < 0$ . Since  $C > (b - A_e)[\gamma e_n](1 - \alpha^2)$ , we have  $\frac{\partial^2 \Pi_e^1(p_n^e, \tau_e)}{\partial \tau_e^2} < 0$ .

Moreover, we know

$$\det(H) = \frac{\partial^2 \Pi_e^1(p_n^e, \tau_e)}{\partial p_n^e{}^2} \cdot \frac{\partial^2 \Pi_e^1(p_n^e, \tau_e)}{\partial \tau_e^2} - \left( \frac{\partial \Pi_e^1(p_n^e, \tau_e)}{\partial \tau_e \partial p_n^e} \right)^2 = 2(\lambda_1 + \chi) \frac{2C}{1 - \alpha^2} \geq (0.5\gamma e_r)^2 - \lambda_1(b - A_e)(\gamma e_r(1 - 4(\lambda_1 + \chi)) - \lambda_1(b - A_e)).$$

Based on the assumption, we know

$$C > [(0.5\gamma e_r)^2 - \lambda_1(b - A_e)(\gamma e_r(1 - 4(\lambda_1 + \chi)) - \lambda_1(b - A_e))] \frac{1 - \alpha^2}{4(\lambda_1 + \chi)}.$$

Therefore,  $\det(H) > 0$ , which implies that  $\Pi_e^1(p_n^e, \tau_e)$  is jointly strictly concave in  $p_n^e$  and  $\tau_e$ . Hence, its maximum value is attained either on the boundary or at the stationary point. To find the stationary point, we solve the following system of linear equalities

$$\frac{\partial \Pi_e^1(p_n^e, \tau_e)}{\partial p_n^e} = 0, \quad \frac{\partial \Pi_e^1(p_n^e, \tau_e)}{\partial \tau_e} = 0.$$

Let  $\Gamma_1 = \frac{(1-\mu)a+w(\lambda_1+\chi)+\chi p_r^m+0.5\gamma(\tau_m e_r-e_n)}{2(\lambda_1+\chi)}$ . Then,  $p_n^e = \Gamma_1 + \Gamma_2 \tau_e$  and

$$\tau_e = \frac{\Gamma_1 0.5\gamma e_r - w 0.5\gamma e_r + (b - A_e)(a - \lambda_1 \Gamma_1 - \lambda_2 p_r^m - \gamma e_n + e_r \gamma \tau_m)}{\frac{2C}{1 - \alpha^2} - \Gamma_2 0.5\gamma e_r - (b - A_e)[2\gamma e_r - \lambda_1 \Gamma_2]}.$$

If  $0 \leq \tau_e \leq 1 - \tau_m$ , then we have found the optimal solution  $(p_n^{e*}, \tau_e^*) = (p_n^e, \tau_e)$ . If  $\tau_e < 0$ , then the optimal solution is  $(\Gamma_1, 0)$ . If  $\tau_e > 1 - \tau_m$ , then the optimal value is  $(\Gamma_1 + \Gamma_2(1 - \tau_m), 1 - \tau_m)$ .

We first assume that  $(p_n^{e*}, \tau_e^*) = (p_n^e, \tau_e)$ . Based on this solution, the manufacturer want to maximize its net profit, which reads

$$\begin{aligned} \Pi_m^1(p_r^m, w, \tau_m) = & w \left[ \frac{(1 - \mu)a - \lambda_1(\Gamma_1 + \Gamma_2 \tau_e^*) - \chi((\Gamma_1 + \Gamma_2 \tau_e^*) - p_r^m)}{-0.5\gamma(e_n - (\tau_m + \tau_e)e_r)} \right] \\ & + p_r^m [\mu a - \lambda_2 p_r^m + \chi((\Gamma_1 + \Gamma_2 \tau_e^*) - p_r^m) - 0.5\gamma(e_n - (\tau_m + \tau_e)e_r)] \\ & - [a - \lambda_1(\Gamma_1 + \Gamma_2 \tau_e^*) - \lambda_2 p_r^m - \gamma(e_n - (\tau_m + \tau_e)e_r)] \\ & [c_m(1 - \tau_m - \tau_e) + c_r(\tau_m + \tau_e) + b\tau_e + A_m \tau_m] \\ & - \frac{C\tau_m^2 + \alpha C\tau_e^2}{1 - \alpha^2} - 0.5K(e_r)^2 \end{aligned}$$

We show that  $\Pi_m^1(p_r^m, w, \tau_m)$  is also jointly strictly concave. To this end, we show that its Hessian is negative definite. As  $\frac{\partial \tau_e}{\partial p_n^e} = \theta$ , we have

$$\begin{aligned} \frac{\partial \Pi_m^1(p_r^m, w, \tau_m)}{\partial p_r^m} = & w \left[ -\lambda_1 \left( \frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2 \theta \right) - \chi \left( \left( \frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2 \theta \right) - 1 \right) + 0.5\theta e_r \right] \\ & + [\mu a - \lambda_2 p_r^m + \chi((\Gamma_1 + \Gamma_2 \tau_e^*) - p_r^m) - 0.5\gamma(e_n - (\tau_m + \tau_e)e_r)] \\ & + p_r^m \left[ -\lambda_2 + \chi \left( \left( \frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2 \theta \right) - 1 \right) + 0.5\theta e_r \right] \\ & - \left[ -\lambda_1 \left( \frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2 \theta \right) - \lambda_2 + \gamma(\theta e_r) \right] [c_m(1 - \tau_m - \tau_e) + c_r(\tau_m + \tau_e) + b\tau_e + A_m \tau_m] \\ & - [a - \lambda_1(\Gamma_1 + \Gamma_2 \tau_e^*) - \lambda_2 p_r^m - \gamma(e_n - (\tau_m + \tau_e)e_r)] [-c_m(\theta) + c_r(\theta) + b\theta] - \frac{2\alpha C \theta \tau_e}{1 - \alpha^2}. \end{aligned}$$

Also,  $\frac{\partial \tau_e}{\partial w} = \delta$ . So,

$$\begin{aligned} \frac{\partial \Pi_m^1(p_r^m, w, \tau_m)}{\partial w} = & [(1 - \mu)a - \lambda_1(\Gamma_1 + \Gamma_2 \tau_e^*) - \chi((\Gamma_1 + \Gamma_2 \tau_e^*) - p_r^m) - 0.5\gamma(e_n - (\tau_m + \tau_e)e_r)] \\ & + w[-\lambda_1(0.5 + \Gamma_2 \delta) - \chi((0.5 + \Gamma_2 \delta)) - 0.5\gamma(-(\delta)e_r)] + p_r^m[\chi((0.5 + \Gamma_2 \delta)) - 0.5\gamma(-(\delta)e_r)] \\ & - [-\lambda_1(0.5 + \Gamma_2 \delta) - \gamma(-(\delta)e_r)] [c_m(1 - \tau_m - \tau_e) + c_r(\tau_m + \tau_e) + b\tau_e + A_m \tau_m] - [a - \lambda_1(\Gamma_1 + \Gamma_2 \tau_e^*) - \lambda_2 p_r^m - \gamma(e_n - (\tau_m + \tau_e)e_r)] \\ & [c_m(-\delta) + c_r(\delta) + b\delta] - \frac{2\alpha C \delta \tau_e}{1 - \alpha^2} \end{aligned}$$

Additionally,  $\frac{\partial \tau_e}{\partial \tau_m} = v$ , which implies that

$$\begin{aligned} \frac{\partial \Pi_m^1(p_r^m, w, \tau_m)}{\partial \tau_m} = & w[-\lambda_1(0.5\gamma e_r + \Gamma_2 v) - \chi((0.5\gamma e_r + \Gamma_2 v)) - 0.5\gamma(-(1 + v)e_r)] + p_r^m[+\chi((0.5\gamma e_r + \Gamma_2 v)) - 0.5\gamma(-(1 + v)e_r)] \\ & - [-\lambda_1(0.5\gamma e_r + \Gamma_2 v) - \gamma(-(1 + v)e_r)] [c_m(1 - \tau_m - \tau_e) + c_r(\tau_m + \tau_e) + b\tau_e + A_m \tau_m] \\ & - [a - \lambda_1(\Gamma_1 + \Gamma_2 \tau_e^*) - \lambda_2 p_r^m - \gamma(e_n - (\tau_m + \tau_e)e_r)] [c_m(-1 - v) + c_r(1 + v) + b\tau_e + A_m] - \frac{2C\tau_m + 2\alpha C v \tau_e}{1 - \alpha^2}. \end{aligned}$$

Therefore, we have

$$\frac{\partial^2 \Pi_m^1(p_r^m, w, \tau_m)}{\partial p_r^m{}^2} = 2 \left( \frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2 \theta \right) (\chi + \lambda_1[-c_m + c_r + b]\theta) + 2\lambda_2([ -c_m + c_r + b]\theta - 1) - 2\chi - 2\gamma\theta^2 e_r[-c_m + c_r + b] - \frac{2\alpha C\theta^2}{1 - \alpha^2}$$

$$\frac{\partial^2 \Pi_m^1(p_r^m, w, \tau_m)}{\partial p_r^m \partial w} = [ -(\lambda_1 + \chi) \left( \frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2 \theta \right) + \chi + 0.5\theta e_r ] + [ \chi(0.5 + \Gamma_2\delta) - 0.5\gamma(-\delta)e_r ] - [ -\lambda_1 \left( \frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2 \theta \right) - \lambda_2 + \gamma(\theta e_r) ] [ c_m(-\delta) + c_r(\delta) + b\delta ] - [ \lambda_1(0.5 + \Gamma_2\delta) - \gamma(-\delta)e_r ] [ -c_m(\theta) + c_r(\theta) + b\theta ] - \frac{2\alpha C\theta\delta}{1 - \alpha^2},$$

$$\frac{\partial^2 \Pi_m^1(p_r^m, w, \tau_m)}{\partial p_r^m \partial \tau_m} = \gamma(1 + \nu)e_r[0.5 - \theta[-c_m + c_r + b]] + (0.5\gamma e_r + \Gamma_2\nu)[\chi + \lambda_1\theta[-c_m + c_r + b]] - \left[ -\lambda_1 \left( \frac{\chi}{2(\lambda_1 + \chi)} + \Gamma_2 \theta \right) - \lambda_2 + \gamma(\theta e_r) \right] [ c_m(-1 - \nu) + c_r(1 + \nu) + b\nu + A_m ] - \frac{2\alpha C\theta\nu}{1 - \alpha^2}$$

$$\frac{\partial^2 \Pi_m^1(p_r^m, w, \tau_m)}{\partial w^2} = 2[ -(\lambda_1 + \chi)(0.5 + \Gamma_2\delta) + 0.5\gamma\delta e_r ] + 2[\lambda_1(0.5 + \Gamma_2\delta) - \gamma\delta e_r][ -c_m + c_r + b]\delta - \frac{2\alpha C\delta^2}{1 - \alpha^2},$$

$$\frac{\partial^2 \Pi_m^1(p_r^m, w, \tau_m)}{\partial w \partial \tau_m} = [ -(\lambda_1 + \chi)(0.5\gamma e_r + \Gamma_2\nu) - 0.5\gamma(-1 + \nu)e_r ] - [ -\lambda_1(0.5 + \Gamma_2\delta) - \gamma(-\delta)e_r ] [ c_m(-1 - \nu) + c_r(1 + \nu) + b\nu + A_m ] - [ -\lambda_1(0.5\gamma e_r + \Gamma_2\nu) - \gamma(-1 + \nu)e_r ] [ c_m(-\delta) + c_r(\delta) + b\delta ] = [ \lambda_1(0.5 + \Gamma_2\delta) - \gamma\delta e_r ] [ c_m(-1 - \nu) + c_r(1 + \nu) + b\nu + A_m ] + (0.5\gamma e_r + \Gamma_2\nu)[ -(\lambda_1 + \chi) + \lambda_1\delta(-c_m + c_r + b) ] + \gamma(1 + \nu)e_r[0.5 - \delta(-c_m + c_r + b)] - \frac{2\alpha C\delta\nu}{1 - \alpha^2},$$

$$\frac{\partial^2 \Pi_m^1(p_r^m, w, \tau_m)}{\partial \tau_m^2} = -2[ -\lambda_1(0.5\gamma e_r + \Gamma_2\nu) + \gamma(1 + \nu)e_r ] [ c_m(-1 - \nu) + c_r(1 + \nu) + b\nu + A_m ] - \frac{2C + 2\alpha C\nu^2}{1 - \alpha^2}.$$

One can see that  $H$  is the Hessian matrix, which is negative definite. Therefore, the maximum value of  $\Pi_m^1(p_r^m, w, \tau_m)$  is attained at the stationary point, or the boundaries. The stationary point is

$$\begin{bmatrix} \bar{p}_r^m \\ \bar{w} \\ \bar{\tau}_m \end{bmatrix} = \frac{1}{\det(H)} \begin{bmatrix} h_{22}h_{33} - h_{23}^2 & -(h_{12}h_{33} - h_{23}h_{13}) & h_{12}h_{23} - h_{22}h_{13} \\ -(h_{12}h_{33} - h_{13}h_{23}) & h_{11}h_{33} - h_{13}^2 & -(h_{11}h_{23} - h_{12}h_{13}) \\ h_{12}h_{23} - h_{13}h_{22} & -(h_{11}h_{23} - h_{13}h_{12}) & h_{11}h_{22} - h_{12}^2 \end{bmatrix} \begin{bmatrix} R_{p_r^m} \\ R_w \\ R_{\tau_m} \end{bmatrix}$$

Therefore, the optimal solution is

$$\tilde{\tau}_m = \begin{cases} 0 & \text{if } \bar{\tau}_m < 0 \\ 1 & \text{if } \bar{\tau}_m > 1 \\ \bar{\tau}_m & \text{otherwise} \end{cases}, \quad \tilde{p}_r^m = \begin{cases} p_{r_0}^{m*} & \text{if } \bar{\tau}_m < 0 \\ p_{r_1}^{m*} & \text{if } \bar{\tau}_m > 1 \\ \bar{p}_r^m & \text{otherwise} \end{cases}, \quad \tilde{w} = \begin{cases} w_0^* & \text{if } \bar{\tau}_m < 0 \\ w_1^* & \text{if } \bar{\tau}_m > 1 \\ \bar{w} & \text{otherwise} \end{cases}.$$

Now, if for the retailer the optimal solution is  $(p_n^*, \tau_n^*) = (\Gamma_1, 0)$ , then  $\nu = \theta = \varphi = \delta = 0$ , and we follow the same calculations to reach to the optimal solution. Furthermore, if for the retailer the optimal solution is  $(p_n^*, \tau_n^*) = (\Gamma_1 + \Gamma_2(1 - \tau_m), 1 - \tau_m)$ , then  $\nu = -1$ ,  $\theta = \delta = 0$ ,  $\varphi = 1$ , and we find the solution similarly. ■

**B.1. Definition of notations**

Let

$$\Gamma_1 = \frac{\left( \chi - \frac{0.5\gamma(b-A_t)\lambda_2 e_r}{2(-(b-A_t)\gamma e_r + \frac{c}{1-\alpha^2})} \right)}{2 \left( \lambda_1 + \chi + 0.5\gamma e_r \frac{\lambda_1(b-A_t)}{2(-(b-A_t)\gamma e_r + \frac{c}{1-\alpha^2})} \right)}$$

$$\Gamma_2 = \frac{(b - A_t)(-\lambda_1\Gamma_1 - \lambda_2)}{2(-(b - A_t)\gamma e_r + \frac{c}{1-\alpha^2})}, \quad \Omega_1 = \frac{1}{2}$$

$$\Omega_2 = \frac{-\lambda_1\Omega_1(b - A_t)}{2(-(b - A_t)\gamma e_r + \frac{c}{1-\alpha^2})}, \quad \Lambda_1 = \frac{0.5\gamma e_r \left( 1 + \frac{(b-A_t)\gamma e_r}{2(-(b-A_t)\gamma e_r + \frac{c}{1-\alpha^2})} \right)}{2 \left( \lambda_1 + \chi + 0.5\gamma e_r \frac{\lambda_1(b-A_t)}{2(-(b-A_t)\gamma e_r + \frac{c}{1-\alpha^2})} \right)}$$

and

$$\Lambda_2 = \frac{(b - A_t)(-\lambda_1\Lambda_1 + \gamma e_r)}{2(-(b - A_t)\gamma e_r + \frac{c}{1-\alpha^2})}.$$

Furthermore, let us set

$$h_{11} = 2(-\lambda_2 + \chi(\Gamma_1 - 1) + 0.5\gamma\Gamma_2 e_r) - 2(-c_m + c_r + b)\Gamma_2(-\lambda_1\Gamma_1 - \lambda_2 + \gamma\Gamma_2 e_r) - \frac{2\alpha C\Gamma_2^2}{1 - \alpha^2},$$

$$h_{12} = (-\lambda_1\Gamma_1 - \chi(\Gamma_1 - 1) + 0.5\gamma\Gamma_2 e_r) + (\chi\Omega_1 + 0.5\gamma\Omega_2 e_r) - (-c_m + c_r + b)\Gamma_2(-\lambda_1\Omega_1 + \gamma\Omega_2 e_r) - (-c_m + c_r + b)\Omega_2(-\lambda_1\Gamma_1 - \lambda_2 + \gamma\Gamma_2 e_r) - \frac{2\alpha C\Gamma_2\Omega_2}{1 - \alpha^2},$$

$$h_{13} = (\chi\Lambda_1 + 0.5\gamma\Lambda_2 e_r) - (-c_m + c_r + b)\Gamma_2(-\lambda_1\Lambda_1 + \gamma\Lambda_2 e_r) - ((-c_m + c_r)(1 + \Lambda_2) + b\Lambda_2 + A_m)(-\lambda_1\Gamma_1 - \lambda_2 + \gamma\Gamma_2 e_r) - \frac{2\alpha C\Gamma_2\Lambda_2}{1 - \alpha^2},$$



$$h_{22} = 2(-(\lambda_1 + \chi)\Omega_1 + 0.5\gamma\Omega_2 e_r) - 2(-c_m + c_r + b)\Omega_2(-\lambda_1\Omega_1 + \gamma\Omega_2 e_r) - \frac{2C\alpha\Omega_2^2}{1 - \alpha^2},$$

$$h_{23} = (-\lambda_1 + \chi)\Lambda_1 + 0.5\gamma(\Lambda_2 + 1)e_r - (-c_m + c_r + b)\Omega_2(-\lambda_1\Lambda_1 + \gamma(\Lambda_2 + 1)e_r) - ((-c_m + c_r)(1 + \Lambda_2) + b\Lambda_2 + A_m)(-\lambda_1\Omega_1 + \gamma\Omega_2 e_r) - \frac{2C\alpha\Omega_2\Lambda_2}{1 - \alpha^2},$$

$$h_{33} = -2((-c_m + c_r)(1 + \Lambda_2) + b\Lambda_2 + A_m)(-\lambda_1\Lambda_1 + \gamma((\Lambda_2 + 1)e_r)) - \frac{C(2 + 2\alpha\Lambda_2^2)}{1 - \alpha^2},$$

$$\phi = \frac{\left( (1 - \mu)a - 0.5\gamma \left( e_n - \left( \frac{(b - A_t)(a - \gamma e_n)}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})} \right) e_r \right) \right)}{2 \left( \lambda_1 + \chi + 0.5\gamma e_r \frac{\lambda_1(b - A_t)}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})} \right)}$$

$$\psi = \frac{(b - A_t)(a - \lambda_1\phi - \gamma e_n)}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})}$$

$$R_{p^m} = (\mu a + \chi\phi - 0.5\gamma(e_n - \psi e_r)) - (-c_m + c_r + b)\Gamma_2(a - \lambda_1\phi - \gamma(e_n - \psi e_r)) - (c_m(1 - \psi) + c_r\psi + b\psi)(-\lambda_1\Gamma_1 - \lambda_2 + \gamma\Gamma_2 e_r) - \frac{2C\alpha\Gamma_2\psi}{1 - \alpha^2},$$

$$R_w = ((1 - \mu)a - \lambda_1\phi - \chi\phi - 0.5\gamma(e_n - \psi e_r)) - (-c_m + c_r + b)\Omega_2(a - \lambda_1\phi - \gamma(e_n - \psi e_r)) - (c_m(1 - \psi) + c_r\psi + b\psi)(-\lambda_1\Omega_1 + \gamma\Omega_2 e_r) - \frac{2C\alpha\Omega_2\psi}{1 - \alpha^2},$$

$$R_{\tau_m} = -((-c_m + c_r)(1 + \Lambda_2) + b\Lambda_2 + A_m)(a - \lambda_1\phi - \gamma(e_n - \psi e_r)) - (c_m(1 - \psi) + c_r\psi + b\psi)(-\lambda_1\Lambda_1 + \gamma((\Lambda_2 + 1)e_r)) - \frac{C(2\alpha\Lambda_2\psi)}{1 - \alpha^2}.$$

**B.2. Proof of Theorem 2.**

As the manufacturer is the leader, the retailer is the follower, and the collector is the follower of the retailer, we first optimize the total net profit obtained by the collector:

$$\Pi_t^2(\tau_t) = (b - A_t)\tau_t D - I_t = (b - A_t)(a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - \tau_m e_r))\tau_t + \left( (b - A_t)\gamma e_r - \frac{C}{1 - \alpha^2} \right) \tau_t^2 - C \frac{\alpha \tau_m^2}{1 - \alpha^2}.$$

As one can see,  $\Pi_t^2(\tau_t)$  is a univariant strictly concave quadratic function, since  $C > (1 - \alpha^2)(b - A_t)\gamma e_r$ . Therefore, we analyze its first derivative to find its maximum:

$$\Pi_t^{2'}(\tau_t) = (b - A_t)(a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - \tau_m e_r)) + 2 \left( (b - A_t)\gamma e_r - \frac{C}{1 - \alpha^2} \right) \tau_t.$$

Hence, the root of  $\Pi_t^{2'}(\tau_t)$  is

$$\bar{\tau}_t = \frac{(b - A_t)(a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - \tau_m e_r))}{2 \left( (b - A_t)\gamma e_r - \frac{C}{1 - \alpha^2} \right)}.$$

Since  $b - A_t > 0$ ,

$$\bar{\tau}_t \leq \frac{(b - A_t)(a - \gamma(e_n - \tau_m e_r))}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})} \leq \frac{(b - A_t)(a - \gamma(e_n - e_r))}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})}$$

Since,  $C > \frac{1 - \alpha^2}{2}((b - A_t)(a - \gamma(e_n - 3e_r)))$ , we have  $\bar{\tau}_t \in (0, 1)$ , which implies that either  $\bar{\tau}_t$  or  $1 - \tau_m$  is the optimal solution.

Now, we maximize the total net profit of the retailer. Let us assume that  $\bar{\tau}_t$  is the optimal collection rate for the collector. Then the total net profit of the retailer is:

$$\Pi_e^2(p_n^e) = (p_n^e - w)D_n^e - s = (p_n^e - w)((1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma(e_n - (\tau_m + \bar{\tau}_t)e_r)) - s.$$

Since  $\bar{\tau}_t$  is a linear function on  $p_n^e$ ,  $\Pi_e^2(p_n^e)$  is a quadratic function. By analyzing its second derivative, we see that  $\Pi_e^2(p_n^e)$  is concave:

$$\Pi_e^{2'}(p_n^e) = ((1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma(e_n - (\tau_m + \bar{\tau}_t)e_r)) + (p_n^e - w) \left( -\lambda_1 - \chi + 0.5\gamma e_r \frac{-\lambda_1(b - A_t)}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})} \right)$$

$$\Pi_e^{2''}(p_n^e) = 2 \left( -\lambda_1 - \chi - 0.5\gamma e_r \frac{\lambda_1(b - A_t)}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})} \right) \leq 0.$$

Therefore, its maximum value is attained at the root of  $\Pi_e^{2'}(p_n^e)$ , which is

$$\bar{p}_n^e = \frac{\left( (1 - \mu)a + \chi p_r^m - 0.5\gamma \left( e_n - \left( \tau_m + \frac{(b - A_t)(a - \lambda_2 p_r^m - \gamma(e_n - \tau_m e_r))}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})} \right) e_r \right) \right)}{2 \left( \lambda_1 + \chi + 0.5\gamma e_r \frac{\lambda_1(b - A_t)}{2(- (b - A_t)\gamma e_r + \frac{C}{1 - \alpha^2})} \right)} + \frac{w}{2}.$$

Hence, the optimal collection rate for the collector is

$$\bar{\tau}_t = \frac{(b - A_t) (a - \lambda_1 \bar{p}_n^e - \lambda_2 p_r^m - \gamma (e_n - \tau_m e_r))}{2(- (b - A_t) \gamma e_r + \frac{C}{1 - \alpha^2})}$$

To maximize the total net profit of the manufacturer, we show that it is jointly strictly concave function. We know that the total net profit of the manufacturer reads

$$\begin{aligned} \Pi_m^2(p_r^m, w, \tau_m) &= wD_n^e + p_r^m D_r^m - c_m(1 - \tau_m - \bar{\tau}_t)D - c_r(\tau_m + \bar{\tau}_t)D - I_m - b\bar{\tau}_t D - A_m \tau_m D - C(e) \\ &= w((1 - \mu)a - \lambda_1 \bar{p}_n^e - \chi(\bar{p}_n^e - p_r^m) - 0.5\gamma(e_n - (\bar{\tau}_t + \tau_m)e_r)) + p_r^m(\mu a - \lambda_2 p_r^m + \chi(\bar{p}_n^e - p_r^m) - 0.5\gamma(e_n - (\bar{\tau}_t + \tau_m)e_r)) \\ &\quad - (c_m(1 - \tau_m - \bar{\tau}_t) + c_r(\tau_m + \bar{\tau}_t) + b\bar{\tau}_t + A_m \tau_m)(a - \lambda_1 \bar{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\bar{\tau}_t + \tau_m)e_r)) \\ &\quad - \frac{C(\tau_m + \alpha \bar{\tau}_t^2)}{1 - \alpha^2} - 0.5K(e_r)^2 \end{aligned}$$

Since  $\frac{\partial \bar{p}_n^e}{\partial p_r^m} = \Gamma_1$ ,  $\frac{\partial \bar{\tau}_t}{\partial p_r^m} = \Gamma_2$ ,  $\frac{\partial \bar{p}_n^e}{\partial w} = \Omega_1$ ,  $\frac{\partial \bar{\tau}_t}{\partial w} = \Omega_2$ ,  $\frac{\partial \bar{p}_n^e}{\partial \tau_m} = \Lambda_1$ , and  $\frac{\partial \bar{\tau}_t}{\partial \tau_m} = \Lambda_2$ , we have

$$\begin{aligned} \frac{\partial \Pi_m^2(p_r^m, w, \tau_m)}{\partial p_r^m} &= w(-\lambda_1 \Gamma_1 - \chi(\Gamma_1 - 1) + 0.5\gamma \Gamma_2 e_r) + (\mu a - \lambda_2 p_r^m + \chi(\bar{p}_n^e - p_r^m) - 0.5\gamma(e_n - (\bar{\tau}_t + \tau_m)e_r)) \\ &\quad + p_r^m(-\lambda_2 + \chi(\Gamma_1 - 1) + 0.5\gamma \Gamma_2 e_r) - (c_m + c_r + b)\Gamma_2(a - \lambda_1 \bar{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\bar{\tau}_t + \tau_m)e_r)) \\ &\quad - (c_m(1 - \tau_m - \bar{\tau}_t) + c_r(\tau_m + \bar{\tau}_t) + b\bar{\tau}_t + A_m \tau_m)(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma \Gamma_2 e_r) - \frac{2C\alpha \Gamma_2 \bar{\tau}_t}{1 - \alpha^2}, \\ \frac{\partial \Pi_m^2(p_r^m, w, \tau_m)}{\partial w} &= ((1 - \mu)a - \lambda_1 \bar{p}_n^e - \chi(\bar{p}_n^e - p_r^m) - 0.5\gamma(e_n - (\bar{\tau}_t + \tau_m)e_r)) + w(-(\lambda_1 + \chi)\Omega_1 + 0.5\gamma \Omega_2 e_r) \\ &\quad + p_r^m(\chi \Omega_1 + 0.5\gamma \Omega_2 e_r) - (c_m + c_r + b)\Omega_2(a - \lambda_1 \bar{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\bar{\tau}_t + \tau_m)e_r)) - (c_m(1 - \tau_m - \bar{\tau}_t) + c_r(\tau_m + \bar{\tau}_t) + b\bar{\tau}_t + A_m \tau_m)(-\lambda_1 \Omega_1 + \gamma \Omega_2 e_r) - \frac{2C\alpha \Omega_2 \bar{\tau}_t}{1 - \alpha^2}, \end{aligned}$$

$$\begin{aligned} \frac{\partial \Pi_m^2(p_r^m, w, \tau_m)}{\partial \tau_m} &= w(-(\lambda_1 + \chi)\Lambda_1 + 0.5\gamma((\Lambda_2 + 1)e_r)) + p_r^m(\chi \Lambda_1 + 0.5\gamma((\Lambda_2 + 1)e_r)) \\ &\quad - ((-c_m + c_r)(1 + \Lambda_2) + b\Lambda_2 + A_m)(a - \lambda_1 \bar{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\bar{\tau}_t + \tau_m)e_r)) \\ &\quad - (c_m(1 - \tau_m - \bar{\tau}_t) + c_r(\tau_m + \bar{\tau}_t) + b\bar{\tau}_t + A_m \tau_m)(-\lambda_1 \Lambda_1 + \gamma((\Lambda_2 + 1)e_r)) \\ &\quad - \frac{C(2\tau_m + 2\alpha \Lambda_2 \bar{\tau}_t)}{1 - \alpha^2}, \end{aligned}$$

$$\begin{aligned} \frac{\partial^2 \Pi_m^2(p_r^m, w, \tau_m)}{\partial p_r^m^2} &= h_{11}, \quad \frac{\partial^2 \Pi_m^2(p_r^m, w, \tau_m)}{\partial p_r^m \partial w} = h_{21}, \quad \frac{\partial^2 \Pi_m^2(p_r^m, w, \tau_m)}{\partial p_r^m \partial \tau_m} = h_{31}, \\ \frac{\partial^2 \Pi_m^2(p_r^m, w, \tau_m)}{\partial w^2} &= h_{22}, \quad \frac{\partial^2 \Pi_m^2(p_r^m, w, \tau_m)}{\partial w \partial \tau_m} = h_{23}, \quad \frac{\partial^2 \Pi_m^2(p_r^m, w, \tau_m)}{\partial \tau_m^2} = h_{33}. \end{aligned}$$

One can see that  $H$  is the Hessian matrix, which is negative definite. Therefore, the maximum value of  $\Pi_m^1(p_r^m, w, \tau_m)$  is attained at the stationary point, or the boundaries. The stationary point is

$$\begin{bmatrix} p_r^m \\ \bar{w} \\ \bar{\tau}_m \end{bmatrix} = \frac{-1}{\det(H)} \begin{bmatrix} h_{22}h_{33} - h_{23}^2 & -(h_{12}h_{33} - h_{23}h_{13}) & h_{12}h_{23} - h_{22}h_{13} \\ -(h_{12}h_{33} - h_{13}h_{23}) & h_{11}h_{33} - h_{13}^2 & -(h_{11}h_{23} - h_{12}h_{13}) \\ h_{12}h_{23} - h_{13}h_{22} & -(h_{11}h_{23} - h_{13}h_{12}) & h_{11}h_{22} - h_{12}^2 \end{bmatrix} \begin{bmatrix} R_{p_r^m} \\ R_w \\ R_{\tau_m} \end{bmatrix}.$$

Therefore, the optimal solution is

$$\bar{\tau}_m = \begin{cases} 0 & \text{if } \bar{\tau}_m < 0 \\ 1 & \text{if } \bar{\tau}_m > 1 \\ \bar{\tau}_m & \text{otherwise} \end{cases}, \quad \bar{p}_r^m = \begin{cases} p_{r0}^{m*} & \text{if } \bar{\tau}_m < 0 \\ p_{r1}^{m*} & \text{if } \bar{\tau}_m > 1 \\ \bar{p}_r^m & \text{otherwise} \end{cases}, \quad \bar{w} = \begin{cases} w_0^* & \text{if } \bar{\tau}_m < 0 \\ w_1^* & \text{if } \bar{\tau}_m > 1 \\ \bar{w} & \text{otherwise} \end{cases}.$$

Now, let  $1 - \tau_m$  be the optimal collection rate for the collector. Then the total net profit of the retailer is:

$$\Pi_e^2(p_n^e) = (p_n^e - w)D_n^e - s = (p_n^e - w)((1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma(e_n - e_r)) - s.$$

Since  $\bar{\tau}_t$  is a linear function on  $p_n^e$ ,  $\Pi_e^2(p_n^e)$  is a quadratic function. By analyzing its second derivative, we see that  $\Pi_e^2(p_n^e)$  is concave:

$$\Pi_e^{2'}(p_n^e) = ((1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma(e_n - e_r)) + (p_n^e - w)(-\lambda_1 - \chi)$$

$$\Pi_e^{2''}(p_n^e) = 2(-\lambda_1 - \chi)$$

Therefore, its maximum value is attained at the root of  $\Pi_e^{2'}(p_n^e)$ , which is

$$\bar{p}_n^e = \frac{((1 - \mu)a + \chi p_r^m - 0.5\gamma(e_n - e_r))}{2(\lambda_1 + \chi)} + \frac{w}{2}.$$

With similar line of reasoning, and resting  $\frac{\partial \bar{p}_n^e}{\partial p_r^m} = \Gamma_1 = \frac{\chi}{2(\lambda_1 + \chi)}$ ,  $\frac{\partial \bar{\tau}_t}{\partial p_r^m} = \Gamma_2 = 0$ ,  $\frac{\partial \bar{p}_n^e}{\partial w} = \Omega_1 = \frac{1}{2}$ ,  $\frac{\partial \bar{\tau}_t}{\partial w} = \Omega_2 = 0$ ,  $\frac{\partial \bar{p}_n^e}{\partial \tau_m} = \Lambda_1 = 0$ , and  $\frac{\partial \bar{\tau}_t}{\partial \tau_m} = \Lambda_2 = -1$ , we have that the optimal solution for the manufacturer is  $(\bar{\tau}_m, \bar{p}_r^m, \bar{w})$ .

C.1. Definitions of notations

Let

$$\delta_1 = \frac{-\lambda_1(b - A_t)}{-2(b - A_t)\gamma e_r + C\frac{2}{1 - \alpha^2}}, \quad \delta_2 = \frac{\gamma e_r(b - A_t)}{-2(b - A_t)\gamma e_r + C\frac{2}{1 - \alpha^2}},$$

$$h_{11}^e = 2(-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r) - C \frac{(2\alpha\delta_1^2)}{1-\alpha^2},$$

$$h_{12}^e = (0.5\gamma(1 + \delta_2)e_r) + (b - A_e)(-\lambda_1 + \gamma\delta_1 e_r) - C \frac{(2\alpha\delta_1\delta_2)}{1-\alpha^2},$$

$$h_{22}^e = 2(b - A_e)(\gamma(1 + \delta_2)e_r) - C \frac{(2 + 2\alpha\delta_2^2)}{1-\alpha^2}.$$

$$C_0 = (2(-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r))(2(b - A_e)(\gamma(1 + \delta_2)e_r)) - ((0.5\gamma(1 + \delta_2)e_r) + (b - A_e)(-\lambda_1 + \gamma\delta_1 e_r))^2,$$

$$C_1 = -(2(-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r)) \left( \frac{(2 + 2\alpha\delta_2^2)}{1-\alpha^2} \right) - \left( \frac{(2\alpha\delta_1^2)}{1-\alpha^2} \right) (2(b - A_e)(\gamma(1 + \delta_2)e_r)) + 2((0.5\gamma(1 + \delta_2)e_r) + (b - A_e)(-\lambda_1 + \gamma\delta_1 e_r)) \left( \frac{(2\alpha\delta_1\delta_2)}{1-\alpha^2} \right),$$

$$C_2 = \left( \frac{(2\alpha\delta_1^2)}{1-\alpha^2} \right) \left( \frac{(2 + 2\alpha\delta_2^2)}{1-\alpha^2} \right) - \left( \frac{(2\alpha\delta_1\delta_2)}{1-\alpha^2} \right)^2.$$

$$\Gamma_0 = -\frac{(b - A_t)\lambda_2}{-2(b - A_t)\gamma e_r + C \frac{2}{1-\alpha^2}},$$

$$\Gamma_1 = -\frac{1}{C_2 C^2 + C_1 C + C_0} (h_{22}^e \chi + h_{12}^e (b - A_e) \lambda_2), \Gamma_2 = -\frac{1}{C_2 C^2 + C_1 C + C_0} (-h_{12}^e \chi - h_{11}^e (b - A_e) \lambda_2),$$

$$\Gamma_3 = \frac{(b - A_t)(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma \Gamma_2 e_r)}{-2(b - A_t)\gamma e_r + C \frac{2}{1-\alpha^2}}, \Omega_1 = -\frac{1}{C_2 C^2 + C_1 C + C_0} (-h_{22}^e (-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r) + h_{12}^e 0.5\gamma(1 + \delta_2)e_r),$$

$$\Omega_2 = -\frac{1}{C_2 C^2 + C_1 C + C_0} (h_{12}^e (-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r) - h_{11}^e 0.5\gamma(1 + \delta_2)e_r)$$

$$\Omega_3 = \frac{(b - A_t)(-\lambda_1 \Omega_1 + \gamma \Omega_2 e_r)}{-2(b - A_t)\gamma e_r + C \frac{2}{1-\alpha^2}}, \Lambda_0 = \frac{(b - A_t)(a - \gamma e_n)}{-2(b - A_t)\gamma e_r + C \frac{2}{1-\alpha^2}}, \Lambda_1 = -\frac{1}{C_2 C^2 + C_1 C + C_0}$$

$$\times \left( h_{22}^e \left( (1 - \mu)a - 0.5\gamma(e_n - \Lambda_0 e_r) - C \frac{(2\alpha\delta_1\Lambda_0)}{1-\alpha^2} \right) \right) - h_{12}^e \left( (b - A_e)(a - \gamma(e_n - \Lambda_0 e_r)) - C \frac{(2\alpha\delta_2\Lambda_0)}{1-\alpha^2} \right)$$

$$\Lambda_2 = -\frac{1}{C_2 C^2 + C_1 C + C_0} \left( -h_{12}^e \left( (1 - \mu)a - 0.5\gamma(e_n - \Lambda_0 e_r) - C \frac{(2\alpha\delta_1\Lambda_0)}{1-\alpha^2} \right) + h_{11}^e \left( (b - A_e)(a - \gamma(e_n - \Lambda_0 e_r)) - C \frac{(2\alpha\delta_2\Lambda_0)}{1-\alpha^2} \right) \right),$$

$$\Lambda_3 = \frac{(b - A_t)(a - \lambda_1 \Lambda_1 - \gamma(e_n - \Lambda_2 e_r))}{-2(b - A_t)\gamma e_r + C \frac{2}{1-\alpha^2}},$$

Also, let

$$R_1^m = (\mu a + \chi \Lambda_1 - 0.5\gamma(e_n - (\Lambda_2 + \Lambda_3)e_r)) - c_m(1 - (\Lambda_2 + \Lambda_3))(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma((\Gamma_2 + \Gamma_3)e_r)) + c_m(\Gamma_2 + \Gamma_3) \\ (a - \lambda_1 \Lambda_1 - \gamma(e_n - (\Lambda_2 + \Lambda_3)e_r)) - (c_r + b)(\Gamma_2 + \Gamma_3)(a - \lambda_1 \Lambda_1 - \gamma(e_n - (\Lambda_2 + \Lambda_3)e_r)) - (c_r + b)(\Lambda_2 + \Lambda_3)(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma((\Gamma_2 + \Gamma_3)e_r)),$$

$$R_2^m = ((1 - \mu)a - \lambda_1 \Lambda_1 - \chi \Lambda_1 - 0.5\gamma(e_n - (\Lambda_2 + \Lambda_3)e_r)) + c_m(\Omega_2 + \Omega_3)(a - \lambda_1 \Lambda_1 - \gamma(e_n - (\Lambda_2 + \Lambda_3)e_r)) \\ - c_m(1 - (\Lambda_2 + \Lambda_3))(-\lambda_1 \Omega_1 + \gamma(\Omega_2 + \Omega_3)e_r) - (c_r + b)(\Omega_2 + \Omega_3)(a - \lambda_1 \Lambda_1 - \gamma(e_n - (\Lambda_2 + \Lambda_3)e_r)) \\ - (c_r + b)(\Lambda_2 + \Lambda_3)(-\lambda_1 \Omega_1 + \gamma(\Omega_2 + \Omega_3)e_r),$$

and

$$h_{11}^m = 2(-\lambda_2 + \chi(\Gamma_1 - 1) + 0.5\gamma((\Gamma_2 + \Gamma_3)e_r)) + 2c_m(\Gamma_2 + \Gamma_3)(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma((\Gamma_2 + \Gamma_3)e_r)) - 2(c_r + b)(\Gamma_2 + \Gamma_3)(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma((\Gamma_2 + \Gamma_3)e_r)),$$

$$h_{12}^m = (-\lambda_1 \Gamma_1 - \chi(\Gamma_1 - 1) + 0.5\gamma(\Gamma_2 + \Gamma_3)e_r) + (\chi \Omega_1 + 0.5\gamma((\Omega_2 - \Omega_3)e_r)) + c_m(\Omega_2 + \Omega_3)(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma((\Gamma_2 + \Gamma_3)e_r)) \\ + c_m(\Gamma_2 + \Gamma_3)(-\lambda_1 \Omega_1 + \gamma(\Omega_2 + \Omega_3)e_r) - (c_r + b)(\Gamma_2 + \Gamma_3)(-\lambda_1 \Omega_1 + \gamma(\Omega_2 + \Omega_3)e_r) \\ - (c_r + b)(\Omega_2 - \Omega_3)(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma((\Gamma_2 + \Gamma_3)e_r)),$$

$$h_{22}^m = 2(-\lambda_1 \Omega_1 - \chi \Omega_1 + 0.5\gamma(\Omega_2 + \Omega_3)e_r) + 2c_m(\Omega_2 + \Omega_3)(-\lambda_1 \Omega_1 + \gamma(\Omega_2 + \Omega_3)e_r) - 2(c_r + b)(\Omega_2 + \Omega_3)(-\lambda_1 \Omega_1 + \gamma(\Omega_2 + \Omega_3)e_r).$$

C.2. Proof of Theorem 3.

To find the optimal prices and collection rates, we start with maximizing the total net profit of the collector, which reads

$$\Pi_t^3(\tau_t) = (b - A_t)\tau_t D - I_t = (b - A_t)\tau_t(a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tau_e + \tau_t)e_r)) - C \frac{(\alpha\tau_e^2 + \tau_t^2)}{1-\alpha^2}.$$

As one can see,  $\Pi_t^3(\tau_t)$  is a univariant strictly concave quadratic function since

$$C > (1 - \alpha^2)(b - A_t)\gamma e_r.$$

Hence, the optimal solution is the stationary point of the function, in case of existence. To find the stationary point, we have:

$$\Pi_t^3(\tau_t) = (b - A_t)(a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tau_e + \tau_t)e_r)) + (b - A_t)\tau_t \gamma e_r - C \frac{(2\tau_t)}{1 - \alpha^2}.$$

Hence, the stationary point is:

$$\bar{\tau}_t = \frac{(b - A_t)(a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - \tau_e e_r))}{-2(b - A_t)\gamma e_r + C \frac{2}{1 - \alpha^2}}.$$

Since  $\bar{\tau}_t \in (0, 1)$ , so the optimal collection rate for the collector is either  $\bar{\tau}_t$  or  $1 - \tau_e$ .

Let us first assume that  $\bar{\tau}_t$  is the optimal collection rate for the collector. Based on this value, we maximize the total net profit of the retailer, which is

$$\Pi_e^3(p_n^e, \tau_e) = (p_n^e - w)D_n^e + (b - A_e)\tau_e D - I_e - s = (p_n^e - w)((1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma(e_n - (\tau_e + \bar{\tau}_t)e_r)) + (b - A_e)\tau_e(a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tau_e + \bar{\tau}_t)e_r)) - C \frac{(\tau_e^2 + \alpha \bar{\tau}_t^2)}{1 - \alpha^2} - s.$$

To maximize  $\Pi_e^3(p_n^e, \tau_e)$ , we first check its concavity status. Since  $\frac{\partial \bar{\tau}_t}{\partial p_n^e} = \delta_1$  and  $\frac{\partial \bar{\tau}_t}{\partial \tau_e} = \delta_2$ , we have

$$\frac{\partial \Pi_e^3(p_n^e, \tau_e)}{\partial p_n^e} = ((1 - \mu)a - \lambda_1 p_n^e - \chi(p_n^e - p_r^m) - 0.5\gamma(e_n - (\tau_e + \bar{\tau}_t)e_r)) + (p_n^e - w)(-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r) + (b - A_e)\tau_e(-\lambda_1 + \gamma\delta_1 e_r) - C \frac{(2\alpha\delta_1 \bar{\tau}_t)}{1 - \alpha^2},$$

$$\frac{\partial \Pi_e^3(p_n^e, \tau_e)}{\partial \tau_e} = (p_n^e - w)(0.5\gamma(1 + \delta_2)e_r) + (b - A_e)(a - \lambda_1 p_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tau_e + \bar{\tau}_t)e_r)) + (b - A_e)\tau_e\gamma(1 + \delta_2)e_r - C \frac{(2\tau_e + 2\alpha\delta_2 \bar{\tau}_t)}{1 - \alpha^2},$$

$$\frac{\partial^2 \Pi_e^3(p_n^e, \tau_e)}{\partial p_n^e{}^2} = h_{11}^e, \quad \frac{\partial^2 \Pi_e^3(p_n^e, \tau_e)}{\partial p_n^e \partial \tau_e} = h_{12}^e, \quad \frac{\partial^2 \Pi_e^3(p_n^e, \tau_e)}{\partial \tau_e^2} = h_{22}^e.$$

Because of the assumptions on C,  $\Pi_e^3(p_n^e, \tau_e)$  is a strictly concave quadratic problem. Hence, its maximum is attained at the stationary point, in case of existence, calculated by

$$\begin{bmatrix} \bar{p}_n^e \\ \bar{\tau}_e \end{bmatrix} = -\frac{1}{C_2 C^2 + C_1 C + C_0} \begin{bmatrix} h_{22}^e & -h_{12}^e \\ -h_{12}^e & h_{11}^e \end{bmatrix} \begin{bmatrix} R_1^e \\ R_2^e \end{bmatrix}.$$

Hence, the optimal solution is

$$\tilde{\tau}_e = \begin{cases} 1 & \text{if } \bar{\tau}_e \geq 1 \\ \bar{\tau}_e & \text{otherwise} \end{cases}, \quad \tilde{p}_n^e = \begin{cases} \frac{-R_1^e - h_{12}^e}{h_{11}^e} & \text{if } \bar{\tau}_e \geq 1 \\ \bar{p}_n^e & \text{otherwise} \end{cases}.$$

Now, if the optimal collection rate for the collector is  $1 - \tau_e$ , then by resetting  $\delta_1 = 0$ ,  $\delta_2 = -1$ , and  $\theta^e = 1$ , we can calculate the optimal solution  $(\tilde{\tau}_e, \tilde{p}_n^e)$ .

Based the solutions obtained, we maximize the total net profit of the manufacturer:

$$\Pi_m^3(p_r^m, w) = wD_n^e + p_r^m D_r^m - c_m(1 - \tilde{\tau}_e - \tau_t)D - c_r(\tau_e + \tau_t)D - b(\tau_e + \tau_t)D - C(e) = w((1 - \mu)a - \lambda_1 \tilde{p}_n^e - \chi(\tilde{p}_n^e - p_r^m) - 0.5\gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) + p_r^m(\mu a - \lambda_2 p_r^m + \chi(\tilde{p}_n^e - p_r^m) - 0.5\gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) - c_m(1 - (\tilde{\tau}_e + \tilde{\tau}_t)) + (a - \lambda_1 \tilde{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) - (c_r + b)(\tilde{\tau}_e + \tilde{\tau}_t)(a - \lambda_1 \tilde{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) - 0.5K(e_r)^2$$

Let us assume that  $\bar{\tau}_e < 1$ ,  $\bar{\tau}_t < 1 - \bar{\tau}_e$ . Since  $\frac{\partial \theta^e}{\partial p_r^m} = \Gamma_0$ ,  $\frac{\partial \tilde{p}_n^e}{\partial p_r^m} = \Gamma_1$ ,  $\frac{\partial \tilde{\tau}_e}{\partial p_r^m} = \Gamma_2$ ,  $\frac{\partial \tilde{\tau}_t}{\partial p_r^m} = \Gamma_3$ ,  $\frac{\partial \tilde{p}_n^e}{\partial w} = \Omega_1$ ,  $\frac{\partial \tilde{\tau}_e}{\partial w} = \Omega_2$ ,  $\frac{\partial \tilde{\tau}_t}{\partial w} = \Omega_3$ , we have:

$$\begin{aligned} \frac{\partial \Pi_m^3(p_r^m, w)}{\partial p_r^m} &= w(-\lambda_1 \Gamma_1 - \chi(\Gamma_1 - 1) + 0.5\gamma(\Gamma_2 + \Gamma_3)e_r) + (\mu a - \lambda_2 p_r^m + \chi(\tilde{p}_n^e - p_r^m) - 0.5\gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) \\ &+ p_r^m(-\lambda_2 + \chi(\Gamma_1 - 1) + 0.5\gamma((\Gamma_2 + \Gamma_3)e_r)) - c_m(1 - (\tilde{\tau}_e + \tilde{\tau}_t))(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma((\Gamma_2 + \Gamma_3)e_r)) \\ &+ c_m(\Gamma_2 + \Gamma_3)(a - \lambda_1 \tilde{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) - (c_r + b)(\Gamma_2 + \Gamma_3)(a - \lambda_1 \tilde{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) \\ &- (c_r + b)(\tilde{\tau}_e + \tilde{\tau}_t)(-\lambda_1 \Gamma_1 - \lambda_2 + \gamma((\Gamma_2 + \Gamma_3)e_r)), \end{aligned}$$

$$\begin{aligned} \frac{\partial \Pi_m^3(p_r^m, w)}{\partial w} &= w(-\lambda_1 \Omega_1 - \chi \Omega_1 + 0.5\gamma(\Omega_2 + \Omega_3)e_r) + ((1 - \mu)a - \lambda_1 \tilde{p}_n^e - \chi(\tilde{p}_n^e - p_r^m) - 0.5\gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) \\ &+ p_r^m(\chi \Omega_1 + 0.5\gamma(\Omega_2 + \Omega_3)e_r) + c_m(\Omega_2 + \Omega_3)(a - \lambda_1 \tilde{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) - c_m(1 - (\tilde{\tau}_e + \tilde{\tau}_t)) \\ &(-\lambda_1 \Omega_1 + \gamma(\Omega_2 + \Omega_3)e_r) - (c_r + b)(\Omega_2 + \Omega_3)(a - \lambda_1 \tilde{p}_n^e - \lambda_2 p_r^m - \gamma(e_n - (\tilde{\tau}_e + \tilde{\tau}_t)e_r)) - (c_r + b)(\tilde{\tau}_e + \tilde{\tau}_t)(-\lambda_1 \Omega_1 + \gamma(\Omega_2 + \Omega_3)e_r). \end{aligned}$$

Hence,  $\frac{\partial^2 \Pi_m^3(p_r^m, w)}{\partial p_r^m{}^2} = h_{11}^m$ ,  $\frac{\partial^2 \Pi_m^3(p_r^m, w)}{\partial p_r^m \partial w} = h_{12}^m$ ,  $\frac{\partial^2 \Pi_m^3(p_r^m, w)}{\partial w^2} = h_{22}^m$ . Based on the assumptions,  $\Pi_m^3(p_r^m, w)$  is strictly concave. Hence, its maximum is attained at a stationary point:

$$\begin{bmatrix} \bar{p}_r^m \\ \bar{w} \end{bmatrix} = -\frac{1}{h_{11}^m h_{22}^m - h_{12}^m{}^2} \begin{bmatrix} h_{22}^m & -h_{12}^m \\ -h_{12}^m & h_{11}^m \end{bmatrix} \begin{bmatrix} R_1^m \\ R_2^m \end{bmatrix}.$$

If  $\bar{\tau}_t > 1 - \bar{\tau}_e$  or  $\bar{\tau}_e > 1$ , then the solution is obtained either when  $\tilde{\tau}_t = 1 - \tilde{\tau}_e$ , or when  $\tilde{\tau}_t = 0$  and  $\tilde{\tau}_e = 1$ . Hence, in the first situation we reset

$$\frac{\partial \tilde{\tau}_t}{\partial p_r^m} = \Gamma_3 = -\Gamma_2, \quad \frac{\partial \tilde{\tau}_t}{\partial w} = \Omega_3 = -\Omega_2, \quad \Lambda_3 = 1 - \Lambda_2,$$

So we can recalculate the solution. In the second situation, we reset

$$\frac{\partial \tilde{p}_n^e}{\partial p_r^m} = \Gamma_1 = \frac{-\chi}{h_{11}^e}, \quad \frac{\partial \tilde{\tau}_e}{\partial p_r^m} = \Gamma_2 = 0, \quad \frac{\partial \tilde{\tau}_t}{\partial p_r^m} = \Gamma_3 = 0,$$



$$\frac{\partial \tilde{p}_n^*}{\partial w} = \Omega_1 = \frac{(-\lambda_1 - \chi + 0.5\gamma\delta_1 e_r)}{h_{11}^e}, \quad \frac{\partial \tilde{\tau}_e}{\partial w} = \Omega_2 = 0, \quad \frac{\partial \tilde{\tau}_i}{\partial w} = \Omega_3 = 0,$$

$$\Lambda_1 = \frac{-((1 - \mu)a - 0.5\gamma e_n) - h_{12}^e}{h_{11}^e}, \quad \Lambda_2 = 1, \quad \Lambda_3 = 0.$$

So we can recalculate the solution. ■

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