

Sourcing from risky reverse channels: Insights on pricing and resilience strategies in sustainable supply chains

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ABSTRACT

This study examines the resilience and sustainability of supply chains amid global disruptions, with a particular focus on the essential role of reverse logistics. Through a game-theoretic approach, we explore manufacturer decisions to source from either reliable but expensive raw materials or cost-effective yet riskier recycled or recyclable materials from the reverse logistics channel. Our analysis outlines three primary sourcing strategies: sourcing exclusively from suppliers (SS), sourcing solely through retailer reverse channel (RS), and a balanced dual sourcing (DS) approach. Our findings reveal the economic viability that recycling outsourcing is influenced by market demand and disruption risks. Notably, in scenarios of constrained market potential, the cost advantage of using recycled materials from less reliable reverse logistics channels surpasses the risks associated with supply chain disruptions, suggesting a complex cost-benefit landscape amidst supply uncertainties. Moreover, the stability of suppliers emerges as a pivotal factor in strategic sourcing decisions, underscoring the need to consider both economic efficiencies and supply reliability. The study also evaluates the dynamic competition between manufacturers and retailers, shedding light on how strategic adjustments driven by sustainability and resilience goals can enhance profitability and sustainability. It was found that despite the threat of disruptions, manufacturers benefit more from engaging with risky reverse channels under specific conditions, underscoring the nuanced decision-making required in uncertain supply scenarios. This research advances sustainable supply chain management by highlighting strategic complexities and the need for understanding economic efficiencies and supply stability, offering insights for navigating disruptions and fostering resilient, sustainable supply chains.

1. Introduction

Sustainable supply chain management (SSCM) relies on efficient management of raw materials and waste reduction to reduce environmental and social impact (Genovese et al., 2017). Recycling has become an attractive, and sometimes necessary, SSCM strategy for cost, environmental, and innovation reasons (Rajabzadeh et al., 2022). Supply chain stakeholders can benefit from recycling (Giri and Dey, 2019). For example, using scrap steel instead of virgin steel can result in a 40% savings in water cost and a 97% reduction in mining waste, and the carbon emissions from using recycled aluminum are a fraction of those from using virgin aluminum because of energy savings (Geng et al., 2019). The recycling industry in the U.S. has resulted in over 1.1 million jobs, \$236 billion in annual income, and \$37 billion in annual wages. On

average, every 10,000 tons of recycled waste generates 36 new jobs (NIH, 2021).

Supply disruption can occur at any stage of a supply chain (Mota et al., 2018). Environmental restrictions, sudden changes in demand, natural disasters, and extreme weather events can each cause supply disruptions (Kumar et al., 2018). Supply disruptions frequently result in poor sales, low return on assets, loss of market share, and weakened competitiveness (Rajabzadeh et al., 2021). For example, in September 2017, the Shanghai local government ordered the closure of Shanghai Jielong Metal Wire Drawing Co., Ltd., the only needle bearings supplier to Schaeffler, a global car parts supplier. Consequently, 49 Chinese manufacturers lost 3 million cars due to a lack of Schaeffler supplies, costing RMB 300 billion (Xu et al., 2020).

Supply chains must be well-prepared to address unpredictable events

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that cause disruption (Rajabzadeh and Babazadeh, 2022). It is necessary to adopt strategies for resilience, which is an organization's ability to recover from disruption (Taleizadeh et al., 2022). Sourcing plays a role in building resilience to disruption. The sourcing process greatly impacted supply chain reactions to the COVID-19 crisis (Frederico et al., 2021). Single-sourcing and multiple-sourcing strategies entered the debate on resilience and managing disruption. Common management wisdom previously viewed single sourcing as strategically wise because of efficiencies and cost savings; the disruptions made this wisdom untenable (Zheng et al., 2022). Sourcing diversification can address various risks from uncertainties including currency exchange rates, supply disruptions, labor strikes, and political instability (Cassidey et al., 2022).

Understanding operational and strategic implications of these situations for organizations and their supply chains is critical not only for long-term competitiveness but also for customer service. From an economic perspective, an organization aiming to operate a sustainable and resilient supply chain must meticulously assess pricing decisions to bolster supply chain financing and investment, particularly concerning sustainability and risk mitigation. These critical considerations are thoroughly examined in this study.

Our investigation concerns the economics of new-product manufacturing relying on recycled materials versus virgin materials. In this study, recycled materials support lower costs and sustainability, but the uncertainties and risks associated with reverse flows tend to be larger than the risks associated with raw-material flows (Fleischmann et al., 1997). To the best of our knowledge, this paper is one of the first to use a game-theoretic approach to investigate the impact of disruptions in the reverse flows of a sustainable supply chain. Managing the risk of disruption is critical for resilience, and sourcing plays a prominent role in a disruption management. This paper examines two types of sourcing methods with resilience issues explicitly considered: (1) dual sourcing from reverse supply channels and the raw-material supplier; and (2) single sourcing from either the retailer's reverse channel or the raw-materials supplier. For the recycling process, two scenarios are examined: Recyclable products collected by the retailer could be recycled by the retailer (Case 1), or they could be sent to the manufacturer to be recycled (Case 2).

Efficient management of raw materials and waste reduction is essential for Sustainable Supply Chain Management (SSCM) to lessen environmental and social impacts. Recycling emerges as a key strategy for its environmental benefits and potential cost savings and innovation. Supply chains face significant disruption risks from environmental regulations, demand shifts, and natural disasters, leading to consequences like reduced sales and competitiveness, exemplified by the 2017 closure of Shanghai Jielong Metal Wire Drawing Co., impacting Chinese car manufacturers significantly (Xu et al., 2020). This research aims to bolster supply chain resilience—the ability to recover from disruptions—by scrutinizing strategic sourcing decisions. The critical role of sourcing in resilience, especially highlighted post-COVID-19, prompts an analysis of the economic viability of using recycled over virgin materials. This study, addressing economic feasibility, risk, and disruptions, is vital for firms focusing on reverse channel recycling and remanufacturing. Our goal is to enhance operational efficiency, compliance, and corporate resilience amid global changes, offering insights into sustainable and resilient supply chain strategies. This research enriches the dialogue on balancing sustainability with economic performance by understanding and mitigating reverse logistics risks.

The remainder of the paper is arranged in the following way. Section 2 has a review of the literature and provides the definitional, practical, and theoretical foundations for this study. Section 3 describes the notation, and model description. Section 4 presents the model formulation and evaluates the game-theoretic results of various sourcing strategies and outcomes. Section 5 has numerical and sensitivity analyses that provide additional insight, with implications for additional research questions. Section 6 presents discussions and managerial insights based

on analyzes. conclusions and suggested future studies are provided in Section 7.

2. Literature review

This literature review is in three parts: resilient, sustainable supply chains; supply disruption and sourcing decisions, and closed-loop supply chain.

2.1. Resilient, sustainable supply chains

Resilient and sustainable supply networks are increasingly important (Ivanov, 2018). Interest in the relationships in sustainable and resilient supply chains has grown—although much greater study is needed to understand the nuances of this relationship (Negri et al., 2021). Sustainability in supply chains is critical for long-term business continuity as resources become depleted (Sarkis and Dou, 2017). Resilient sustainable supply chains reduce risks of disruption (Negri et al., 2021). To mitigate supply chain disruptions, product demand may be met by combining sustainability and resilience (Fahimnia and Jabbarzadeh, 2016). In this regard, Majumdar et al. (2021) investigated the prioritization of disruption-mitigation strategies in the context of an environmentally sustainable clothing supply chain, with a focus on evaluating their effectiveness in mitigating diverse disruptions. Kaur et al. (2020) demonstrated that integrating a production and procurement model that considers market demand uncertainties, supplier and carrier capacities, and environmental impacts, including carbon emissions, can lead to a "triple win" for supply chains. This approach simultaneously enhances sustainability, resilience, and cost-effectiveness.

The integrative and analytical investigation of resilience and sustainability has been important for a variety of industries with risky disruptive environments such as built materials (Jabbarzadeh et al., 2018) and pharmaceuticals (Zahiri et al., 2017). Various environmental and external relationships affect supply network resilience and sustainability with properties such as ripple effects and diffusion, adding complexity that goes beyond pricing considerations (Ivanov, 2018). Even with these various contexts, linking sustainability and resilience from a business and supply chain perspective is still immature and requires significantly more research (Negri et al., 2021).

2.2. Supply disruption and sourcing decisions

Supply disruptions have always had a detrimental impact on supplier capacity to fulfill orders (Gupta and Ivanov, 2020). Retailers and manufacturers use a variety of sourcing strategies to avoid supply shortages—including single, dual, and multiple sourcing (Luo et al., 2021). The effect of supply disruption is well-known and may be severe, but sourcing strategies have received relatively limited attention in the literature. A number of studies explore supply disruptions and sourcing choices, providing insights into several areas: flexible sourcing and pricing strategies (Kumar et al., 2018; Wang and Yu, 2020); supplier characteristics (Giri and Sharma, 2016; Azad and Hassini, 2019; Gupta and Ivanov, 2020); the ability to recover and a capacity for alerting buyers (Namdar et al., 2018); and disruption cases resulting in complete supplier shutdown (Freeman et al. (2018).

Contingent sourcing and multiple sourcing help to manage the risk of supply disruption in a competitive setting where a competitor may have a more dependable supply (Kumar et al., 2018). Contingent sourcing, as with all sourcing approaches, can be integrated with various pricing strategies in order to minimize supply disruptions (Wang and Yu, 2020).

Strategic sourcing decisions can also arise from the characteristics of the suppliers (Giri and Sharma, 2016). For example, disruption and resilience sourcing characterizations may include a supplier strategy where one supplier may be cheaper but unreliable, while a secondary supplier is reliable but more costly. Whether to source or manufacture products is also a sourcing decision; optimization models—not just

game-theoretic approaches—have recently addressed this issue e.g. (Azad and Hassini, 2019). An optimal strategy in many cases is derived from hybrid in-house and outsourcing decisions. Using game-theoretic approaches, supplier characteristics such as risk propensity have also been studied (Gupta and Ivanov, 2020).

In the supply chain investigated by Freeman et al. (2018), one crucial component was a supplier who had a specified likelihood of failure to deliver required components. The manufacturer used several sourcing tactics to reduce the risk of an unreliable source. In addition to contingent sourcing, extra safety inventories and backorders were also a strategy for managing disruptions.

2.3. Closed-loop supply chain

Closed-loop supply chains (CLSCs) are increasingly recognized for embedding sustainability within business operations, highlighting the necessity of maximizing resource efficiency through reintegrating goods for recycling or remanufacturing (Mishra et al., 2023). While CLSCs offer significant environmental benefits, they introduce complexities in pricing strategy formulation due to the variable quality and conditions of returned products (Beranek and Buscher, 2023). The inherent uncertainty of reverse logistics within CLSCs poses disruption risks, potentially affecting the availability of recyclable materials and influencing the pricing dynamics of new versus remanufactured products (Mishra and Singh, 2020; Abbey et al., 2015).

Understanding the interplay between pricing strategies and disruption risks is crucial for sustaining economic viability and environmental integrity within CLSCs. The importance of accommodating fluctuations in the quality and supply of returned goods in pricing decisions has been highlighted by Jafari et al. (2017), noting that such variability can disrupt supply chain operations. Further, Rajabzadeh et al. (2022) have shown that strategic pricing and return policies can effectively mitigate the economic impacts of supply chain disruptions.

Recent advancements in research, such as those by Gaur et al. (2020), advocate for the development of more resilient CLSC models capable of foreseeing and managing disruption risks through advanced analytical techniques to enhance the predictability of return flows. The pivotal role of pricing in navigating these uncertainties is underscored by Tang (2006), who advocates for adaptable pricing models responsive to the flux of returned product volumes.

Table 1 has a summary of the literature that shows some of the characteristics of each study. Then, the gaps covered by this study is investigated comparing to most related papers as Table 2.

Based on the provided gaps above, this study employs a game-theoretic approach to analyze pricing decisions while contributing to the literature by simultaneously addressing resilient and sustainable supply chain considerations. The model in this study considers three levels of investigation: the raw-materials supplier, the manufacturer,

Table 2
The most relevant previous studies and the related research gaps.

Article	Gaps
Giri and Sharma (2016)	Both our study and the research by Giri and Sharma (2016) optimize closed-loop supply chains by considering recycling and dual sourcing to mitigate risks. Our work expands on theirs by introducing pricing strategies for recycled products and addressing the challenges in reverse logistics, which is more prone to disruptions.
Giri and Dey (2019)	Although this paper studied pricing using a game-theoretic approach in a forward logistic disruptive closed-loop supply chain considering dual sourcing with a backup supplier, it did not consider the disruption probability and its effect on sourcing strategies, resulting in just dual sourcing. In our study, by considering the statistical nature of disruption probability, the sourcing strategy varies based on disruption probability (dual sourcing and single sourcing). Additionally, they failed to consider disruptions in the reverse channel, which were only considered in forward logistics.
Kumar et al. (2018)	Considering a disruptive forward logistic, Kumar et al. (2018) investigated the pricing and sourcing strategies in different probabilities of disruption using a game theoretic approach. However, unlike our model, sustainability factors, including reverse logistics and recycling, were never taken into account in their study. Additionally, disruptions were only considered for forward logistics.
Beranek and Buscher (2023)	Like our model, the authors studied pricing issues using a game theory approach in a closed-loop supply chain where the return rate is considered random in two distinctive cases: returns only to the retailer and returns only to the manufacturer. The main difference between their model and ours is that they did not consider resilience options like various sourcing strategies, nor did they investigate how disruptions in reverse logistics might affect retail prices in forward logistics, all of which are considered in our study.

and the retailer. This is a multi-tier perspective that is not well investigated in the literature. Reverse logistics is considered in this study where the retailer is assumed to collect (take back) used products for recycling. After the retailer collects the used products, the collected products are then recycled by the retailer before sending the materials to the manufacturer (Case 1) or sent to the manufacturer and then recycled by the manufacturer (Case 2).

The manufacturer can produce products from recycled used products (and materials) at lower production costs but from an unreliable channel or/and it can produce products using raw materials with higher production cost supplied through a reliable channel—as informed by previous quality-of-materials studies (Kumar et al., 2018). This study represents one of the initial efforts to analyze the risk of disruption in reverse logistics and its impact on resilience decisions. Specifically, this study focuses on the choice between single sourcing (relying solely on either the reverse logistics channel or the raw-materials supplier) and

Table 1
Summary of the literature review.

Reference	Pricing	Disrupted Logistic	Sourcing		Recycling	CLSC	Approach	Game Structure	
			Unit	Strategy				S	N
Kumar et al. (2018)	✓	FL	R	DS-SS			Game theory	✓	✓
Li et al. (2021)	✓	FL	M	DS			Control Theory		
Wang and Yu (2020)	✓	FL	R	DS-SS			Responsive/Committed pricing		
Azad and Hassini (2019)	✓	FL	M-R	SS-MS			Benders decomposition		
Giri and Sharma (2016)	✓	FL	M	DS	✓	✓	Non-linear programming		
Gupta and Ivanov (2020)	✓	FL	R	DS			Game theory		
Gupta et al. (2021)	✓	FL	R	DS			Game theory	✓	✓
Freeman et al. (2018)	✓	FL	M	MS			Stochastic programming		
Giri and Dey (2019)	✓	FL	M	DS	✓		Game Theory	✓	✓
Gheibi and Fay (2021)	✓	FL	R	DS			Non-linear programming		
Beranek and Buscher (2023)	✓	RL			✓	✓	Game Theory	✓	
This paper	✓	RL	M	DS-SS	✓	✓	Game theory	✓	

FL: Forward Logistic, RL: Reverse Logistic, R: Retailer, M: Manufacturer, SS: Single Sourcing, DS: Dual Sourcing, MS: Multiple Sourcing, S: Stackelberg, N: Nash.

dual sourcing (sourcing from both the reverse logistics channel and the raw-materials supplier) for a manufacturer operating as a price taker. None of the previous studies have considered reverse logistics elements—especially environmentally sustainable recycling practices—and their relationship to disruption. This situation becomes even more important as shown in the COVID environment, where many products needed to be repaired not only for profitability but also for the livelihood of consumers.

The motivations of this study and the contributions it adds to the literature are as follows:

Motivations for Research Objectives.

- 1. Dynamic Sourcing Strategies:** filling the existing research gap by creating flexible sourcing methods that can effectively react to the probability of disruptions, therefore improving the overall resilience of the supply chain.
- 2. Comprehensive Reverse Logistics:** incorporating reverse logistics into supply chain models aims to tackle disruptions and enhance the efficiency of recycling operations, thereby addressing a significant need in current research.
- 3. Advanced Pricing for Recycled Products:** Developing novel pricing techniques for recycled items that accurately represent their intrinsic worth and effectively foster sustainability in closed-loop supply chains.

Significance of Contribution.

- 1. Robust Supply Chain Framework:** Provides a more complete and integrated approach to the supply chain, including both forward and reverse logistics, and offers valuable theoretical and practical insights.
- 2. Improved Risk Management and Efficiency:** Improves the resilience and efficiency of the supply chain by using adaptable sourcing methods and efficiently managing reverse logistics.
- 3. Sustainability and Economic Benefits:** Enhances sustainability via the optimization of recycling procedures and pricing strategies, so contributing to both environmental objectives and economic feasibility.

3. Notation, problem statement and assumptions

Notation

The notation used in this paper is listed in Table 3.

3.1. Problem statement

The supply chain and reverse logistics (channel) elements in this study consist of a manufacturer, a retailer, and a supplier (Fig. 1). The manufacturer produces new products and sells them to the retailer at a wholesale price of w_{li}^j . The retailer sells new products to customers at a price of p_{li}^j . The retailer benefits from the reverse channel, which means that the used products can be collected by the retailer and transferred back at a price of t_l to the manufacturer. The manufacturer benefits from the supplier, who can supply the manufacturer with raw materials at a price of p_s . Therefore, the manufacturer has the option of producing new products either with recycled materials or with raw materials.

The difference between the retailer reverse channel, and the supplier forward channel is the assumption that recycled-material product costs (c_r) are lower than raw-material product costs (c_m) (Savaskan et al., 2004). However, the raw-materials supplier is assumed to be more reliable than receiving recycled materials from the reverse channels, which have higher probabilities of disruption. As a result, the manufacturer can supply its requirements to produce new products from a risky supplier with low production cost from a reverse channel or a

Table 3
Notation used for model and formulation.

Category	Symbol	Definition	
Nomenclatures	m	The manufacturer	
	r	The retailer	
	$i = \begin{cases} n \\ d \end{cases}$	Non-disruption Disruption	
	$j = \begin{cases} DS \\ SR \\ SS \end{cases}$	Dual sourcing Sourcing from the retailer Sourcing from the supplier	
	$l = \begin{cases} 1 \\ 2 \end{cases}$	Case 1 Case 2	
	Parameters	c_m	Production cost from raw materials (Euro)
		c_r	Production cost from recycled materials (Euro)
c_u		Recycling cost handled by the retailer (Euro)	
c_v		Recycling cost handled by the manufacturer (Euro)	
p_s		The unit price of raw material (Euro/product)	
t_l		The transfer price for the retailer in Case l (Euro/product)	
θ		The recyclability degree of the used products ($0 < \theta < 1$)	
ϵ		The amount of raw materials needed to produce a unit of new product ($\epsilon > 1$)	
$\frac{\epsilon}{\theta}$		The quantity of the recyclable used products required to produce a unit of new product	
a		The market potential of the retailer	
b		Own-price elasticity of retailer	
β		Scale parameter	
q		The disruption probability of retailer's reverse channel $0 < q < 1$	
Decision variables	w_{li}^j	The wholesale price of the manufacturer in case l mode i strategy j (Euro/product)	
	p_{li}^j	The retail price of the new product in case l mode i strategy j (Euro/product)	
	α_l	The split of the order to the retailer in case l $0 \leq \alpha_l \leq 1$, where $\alpha_l = 1$ implies SR and $\alpha_l = 0$ denotes SS.	
Functions	λ_l	K.K.T coefficient in case l	
	D	Customer demand function	
	I	Retailer investment function for used products collection (Euro)	
	$\pi_{l,m}^j$	Manufacturer profit function for strategy j case l (Euro)	
	$\pi_{l,r}^j$	Retailer profit function for strategy j case l (Euro)	



Fig. 1. A schematic representation of the proposed model.

reliable supplier with high production cost from raw materials. Generally, the manufacturer prefers to produce new products from recycled materials for two reasons: using recycled materials allows the manufacturer to pay less for new-product production costs, and recycled materials provide environmentally friendly material (Giri and Dey, 2019). The shift toward sustainable supply chains is no longer just a trend; it is a necessity for companies across the globe. In fact, some of the biggest players in the industry have already set ambitious sustainability goals. For example, Dell has announced that by 2030, they plan to reuse or recycle an equivalent product for every product a customer buys. Moreover, they aim to make 100% of their packaging from recycled material and use more than half of recycled material in their products (Dell, 2023). Another notable example is Nike, which has been incorporating recycled materials into their products for years. In 2020, they launched the Space Hippy sneaker, which was made from an impressive 85–90% recycled materials (Nike, 2023).

In our study, there is no difference in product quality between new products produced with recycled materials and new products produced with raw materials (Ranjbar et al., 2020). Fig. 1 provides a schematic representation of the proposed model, which includes all players involved in the studied supply chain.

The probability of disruption of the retailer’s reverse channel is ‘ q ’; the assumption is that, in the case of disruption, the retailer’s reverse channel cannot supply any recycled or collected used products. Rather than receiving recycled or collected used materials in small batches throughout the selling season, materials are received in bulk at the beginning of the selling season, resulting in a lack of supply during times of disruption. The timeline of the events is presented in Fig. 2.

Using the timeline of events in Fig. 2, the manufacturer chooses its best sourcing strategy by being aware of the probability of disruption. If the disruption state is realized at the end of the order lead time, the manufacturer updates its wholesale prices. Then, the retailer updates its new-product prices.

There are three strategies that can be chosen by the manufacturer for sourcing based on the probability of disruption in the reverse logistics channel. It is worth noting that in the proposed model, when $q = 1$, it indicates a complete disruption of the reverse channel, with a probability of 100%. However, in situations where the probability of disruption q is less than 1, there is a critical threshold point for the value of q at which the manufacturer makes the decision to switch from single sourcing in the reverse channel to dual sourcing, or vice versa. In other words, there is a specific point where if q becomes lower than this point, the manufacturer will source only from the reverse channel, and if q becomes higher than this point, the manufacturer will choose a dual-sourcing strategy. This specific point is named δ , known in this study as the critical probability of disruption. This threshold is very important in terms of understanding the dynamics of sourcing decisions and resilience strategies in a sustainable supply chain.

The properties of δ are explored in detail in subsequent sections. How the optimal sourcing strategy changes with δ is represented diagrammatically in Fig. 4.

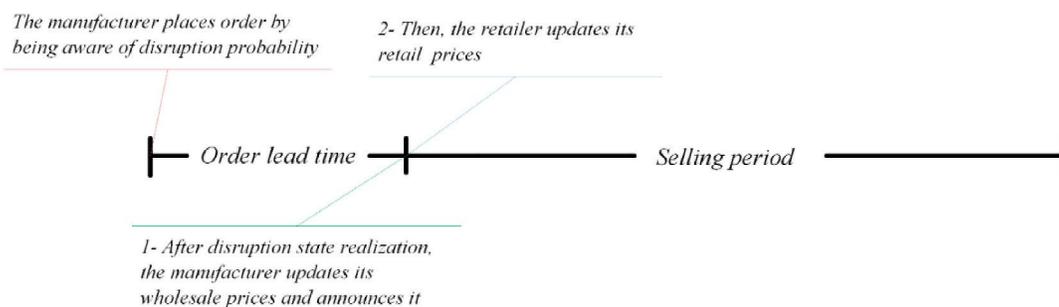


Fig. 2. The timeline of events.

- 1) **Dual sourcing (DS):** This is the current and main strategy. It occurs when $\delta < q < 1$. In this situation, the manufacturer splits its order between the reverse logistics channel (α_l) and the supplier ($1 - \alpha_l$) based on the disruption risk (Fig. 3a).
- 2) **Sourcing only from the retailer (SR):** This strategy will be chosen when $q \leq \delta$. In this situation, the manufacturer prefers to supply from the reverse logistics channel (Fig. 3b).
- 3) **Sourcing only from the supplier (SS):** This strategy is applicable when $q = 1$. In this situation, the retailer cannot supply the manufacturer, and the manufacturer must supply only from the supplier (Fig. 3c).

Since the manufacturer sets its reverse logistics channel demand from the retailer as the split (α_l) of the order, it can be inferred that for the retailer, (α_l) is the optimal returns demand. Consequently, based on the returns demand set by the manufacturer, the retailer invests in collection efforts (I) and collects used products.

The retailer’s investment (I) in collecting used products is given by Eq. (1) (Savaskan and Van Wassenhove, 2006).

$$I = \beta(\alpha_l)^2 \tag{1}$$

where α_l is the manufacturer’s demand for returns of used products, and β is a scaling parameter.

Fig. 4 shows the graph of (α_l) as a function of the risk of disruption in the reverse logistics channel (q).

The demand function in this study is linearly dependent on the product’s price. This type of demand function has widespread use in academic literature (Assarzadegan and Rasti-Barzoki, 2019).

$$D = a - bp_{li}^j \tag{2}$$

where a is the market potential of the retailer, b is the own-price elasticity, and p_{li}^j is the retail price.

It is assumed that both the retailer and the manufacturer are able to recycle collected used products.

Using these scenarios, we model two cases:

Case 1: In this case, the collected products are recycled by the retailer at a cost c_u and sent to the manufacturer with a transfer price of t_1 .

Case 2: In this case, the collected products are sent to the manufacturer at a transfer price of t_2 lower than t_1 , and the manufacturer recycles them at a cost of c_v , higher than c_u . In our analysis, we’ve drawn on the cost structure models from Jafari et al. (2017); Giri and Dey (2019); Heydari et al. (2017), all of which are based on real-world case studies. These models provide a solid foundation that mirrors recycling operations’ practical and financial aspects within actual supply chain contexts.

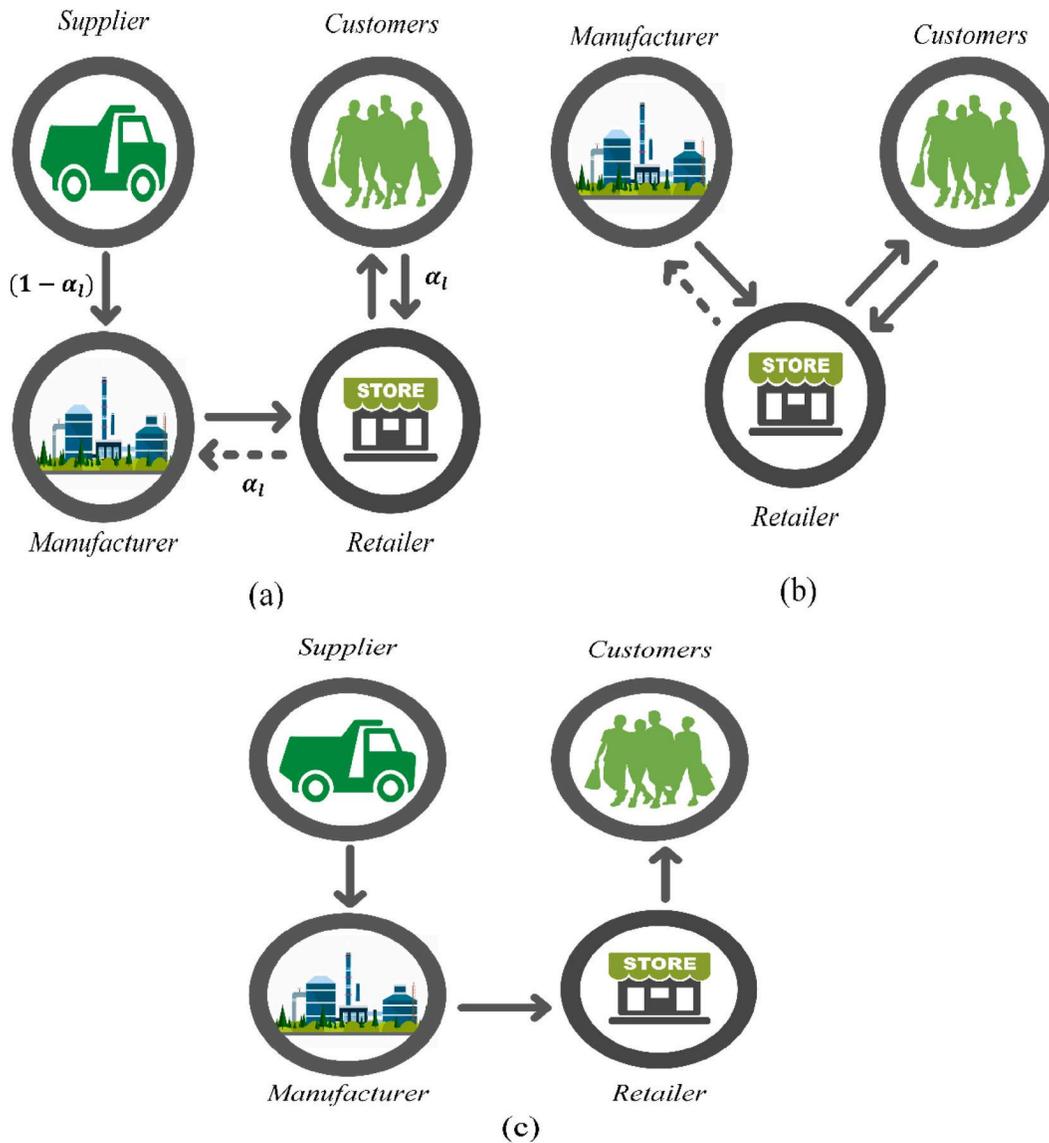


Fig. 3. Diagrammatic representations of the three sourcing strategies considered: (a) dual sourcing strategy, (b) sourcing from the retailer, (c) sourcing from the supplier.

3.2. Assumptions

3.2.1. Cost of recycled vs. new raw materials

- **Assumption:** Recycled materials (c_r), cost less than new raw materials (c_m).
- **Justification:** Supported by Savaskan et al. (2004), the cost benefit stems from reduced expenses in procurement and processing, as well as the use of more energy-efficient recycling methods. Additionally, environmental incentives promote the utilization of recycled materials.
- **Impact on Model:** Influences cost parameters, affecting our analysis of economic viability and sustainability in supply chain decisions.

3.2.2. Reliability of raw-material suppliers compared to reverse logistics

- **Assumption:** Raw-material suppliers are more reliable than reverse logistics channels, which are prone to higher disruption risks.
- **Justification:** Conventional supply chains are characterized by their stability and predictability since they include long-term collaborations and maintain continuous quality (Jayasinghe et al., 2022; XU

et al., 2020). On the other hand, reverse logistics channels exhibit more instability because of fluctuating quality, reliance on customer recycling habits, and intricate processing demands.

- **Impact on Model:** Essential for assessing the probability of disruptions in supply chain resilience and making strategic sourcing choices.

3.2.3. Impact of disruptions in reverse logistics

- **Assumption:** Disruptions in reverse logistics significantly impact the supply of recycled or used items, potentially halting the supply chain.
- **Justification:** The reverse supply chain is intricately linked, with a strong dependence on the collection, transportation, and processing of products. Disruptions may lead to a cascade of consequences, making it difficult to adhere to recycling standards and laws without sufficient contingency preparations or alternate pathways (Kumar et al., 2018).
- **Impact on Model:** Explores the stability and risk management techniques in the supply chain, emphasizing the potential risks associated with depending only on reverse logistics.

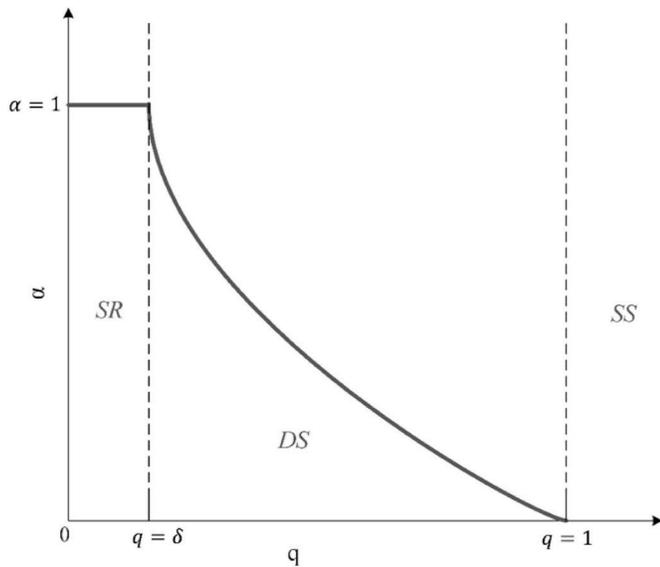


Fig. 4. The graph of α_1 as a function of q .

3.2.4. Recycling capabilities of retailers and manufacturers

- **Assumption:** Both retailers and manufacturers can effectively recycle used products, as evidenced in specific industries.
- **Justification:** A widespread technique in sectors, such as plastic cup manufacture, involves the recycling of materials such as polypropylene (PP) and polyethylene terephthalate (PET). Some examples of companies that engage in the recycling of discarded plastic bottles to create new items are Tony Guo Xiamen Taryn Industry & Trade and Vera LI Yiwu Green Commodity (Shah et al., 2008; Jafari et al., 2017).
- **Impact on Model:** Demonstrates the realistic possibility of implementing recycling activities in the model and emphasizes the sustainability component of the supply chain.

4. Model formulation and optimal values

4.1. Case 1: Supply recycled materials from the reverse channel of the retailer

The profit functions and the optimal values of decision variables in each sourcing strategy—dual sourcing (DS), sourcing from the retailer (SR), and sourcing from the supplier (SS)—are developed and presented below.

4.1.1. Dual sourcing (DS)

Considering all assumptions and the model definition, in this case, the profit functions of the manufacturer ($\pi_{1,m}^{DS}$), and the retailer ($\pi_{1,r}^{DS}$) are shown in Eq. (3) and Eq. (4), respectively.

$$\begin{aligned} \pi_{1,m}^{DS} = & (1 - q) \left(w_{1,n}^{DS} - \varepsilon(1 - \alpha_1)c_m - \varepsilon(1 - \alpha_1)p_s - \varepsilon\alpha_1c_r - \varepsilon\alpha_1t_1 \right) (a - bp_{1,n}^{DS}) \\ & + q \left(w_{1,d}^{DS} - \varepsilon c_m - \varepsilon p_s \right) (a - bp_{1,d}^{DS}) \\ & \text{s.t.} \\ & (1 - \alpha_1) \left(a - bp_{1,d}^{DS} \right) \geq \left(a - bp_{1,d}^{DS} \right) \end{aligned} \quad (3)$$

$$\begin{aligned} \pi_{1,r}^{DS} = & (1 - q) \left(p_{1,n}^{DS} - w_{1,n}^{DS} + \varepsilon\alpha_1 \left(t_1 - \frac{1}{\theta}c_u \right) \right) (a - bp_{1,n}^{DS}) + q \left(p_{1,d}^{DS} \right. \\ & \left. - w_{1,d}^{DS} \right) (a - bp_{1,d}^{DS}) - \beta(\alpha_1)^2 \end{aligned} \quad (4)$$

The manufacturer's profit function ($\pi_{1,m}^{DS}$) consists of two parts,

starting with $(1 - q)$ for non-disruption mode and q for disruption mode as parts one and two, respectively. Part one, multiplied by the demand function in non-disruption mode, shows the manufacturer's revenue from selling produced new products in a non-disruption mode; it uses the wholesale price ($w_{1,n}^{DS}$), the cost of production from raw materials (c_m) and the unit price of the raw material supplier (p_s), which both are dependent on the split of the order to the raw material supplier ($1 - \alpha_1$) and the amount of raw materials needed to produce a unit of new product (ε). Moreover part one includes also the cost of production from recycled materials (c_r) and transfer price of the retailer (t_1), which both are dependent on the split of the order to reverse channel of the retailer (α_1) and ε .

The second part, multiplied by the demand function in disruption mode, represents the manufacturer's revenue in disruption mode; it uses the wholesale price ($w_{1,d}^{DS}$), the cost of production from raw materials (c_m) and the unit price of the raw material supplier (p_s), which both are dependent on ε . The constraint in Eq. (3) guarantees that the raw materials ordered from the supplier at the beginning of the will be received even if disruption happens.

The profit function of the retailer ($\pi_{1,r}^{DS}$) has three parts. The first part multiplied by the demand function in non-disruption mode, which is for non-disruption mode shown by $(1 - q)$, shows the retailer's revenue from selling new products to the customers at price $p_{1,n}^{DS}$ and transferring the recycled materials to the manufacturer (t_1) which is dependent on α_1 and ε .besides, there is a purchase cost of new products ($w_{1,n}^{DS}$). Since the retailer recycles the collected, used products, it includes the cost of recycling as well (c_u) which is dependent on The quantity of the recyclable used products required to produce a unit of new product ($\frac{1}{\theta}$).

The second part, multiplied by the demand function in disruption mode, addresses a scenario where the retailer's reverse channel faces disruption, which means that there is no income from transferring recycled materials to the manufacturer, relying solely on revenue from selling new products to customers at price $p_{1,d}^{DS}$ and cost of $w_{1,d}^{DS}$. The last part is the retailer's expenditure in collecting used products, which is directly relies on the manufacturer's split of the order form the retailer (α_1).

4.1.2. Sourcing from the retailer (SR)

Based on the definitions and assumptions, the profit functions of the manufacturer and the retailer appear in (5) and (6), respectively.

$$\pi_{1,m}^{SR} = (1 - q) \left(w_{1,n}^{SR} - \varepsilon c_r - \varepsilon t_1 \right) (a - bp_{1,n}^{SR}) \quad (5)$$

$$\pi_{1,r}^{SR} = (1 - q) \left(p_{1,n}^{SR} - w_{1,n}^{SR} + \varepsilon \left(t_1 - \frac{1}{\theta}c_u \right) \right) (a - bp_{1,n}^{SR}) - \beta \quad (6)$$

The profit function of the manufacturer ($\pi_{1,m}^{SR}$) in this strategy which is multiplied by the demand function in non-disruption mode, consists of only one part, since the manufacturer prefers to supply only from the retailer. This part shows the manufacturer's revenue from selling new products to the retailer and includes the wholesale price ($w_{1,n}^{SR}$), the cost of production from recycled materials (c_r), and the cost to transfer recycled materials (t_1), which both are dependant to.

The retailer's profit function ($\pi_{1,r}^{SR}$) has two parts. The first part multiplied by the demand function in non-disruption mode, shows the income from selling new products to customers at a price $p_{1,n}^{SR}$ and transferring recycled products to the manufacturer at price of t_1 dependant to. It also includes recycling costs (c_u) dependant on ($\frac{1}{\theta}$). since the retailer also recycles used products. The second part shows the retailer's investment in collecting used products (β).This is the retailer's expenditure in collecting used products in DS mode ($\beta(\alpha_1)^2$) since in this sourcing strategy α_1 equals one, the retailer's investment in collecting used products becomes β .

4.1.3. Sourcing from the supplier (SS)

The profit functions of the manufacturer and the retailer when sourcing from a raw-materials supplier are presented in (7) and (8), respectively.

$$\pi_{1,m}^{SS} = (w_{1,d}^{SS} - \epsilon c_m - \epsilon p_s) (a - bp_{1,d}^{SS}) \quad (7)$$

$$\pi_{1,r}^{SS} = (p_{1,d}^{SS} - w_{1,d}^{SS}) (a - bp_{1,d}^{SS}) \quad (8)$$

The manufacturer's profit function ($\pi_{1,m}^{SS}$) includes the manufacturer's income from selling new products multiplied by the demand function in disruption mode. It includes the wholesale price ($w_{1,d}^{SS}$), the cost of production from raw materials (c_m), and the unit price of raw materials (p_s) both of which dependant on. The retailer's profit function ($\pi_{1,r}^{SS}$) only includes revenue from selling new products multiplied by the demand function in disruption mode. It includes the retail price ($p_{1,d}^{SS}$), and the purchase cost of new products from the manufacturer ($w_{1,d}^{SS}$).

4.2. Case 2: Supply recyclable materials from the reverse channel of the retailer

In Case 2, the supplied materials are recyclable, but not yet recycled. Similar to Case 1, each sourcing strategy is also studied in this case. The profit functions, optimal responses, and values are summarized in subsections based on the sourcing strategy.

4.2.1. Dual sourcing (DS)

The profit functions of the manufacturer ($\pi_{2,m}^{DS}$), and the retailer ($\pi_{2,r}^{DS}$) for the dual-sourcing strategy for Case 2 appear in Eqs. (9) and (10), respectively.

$$\begin{aligned} \pi_{2,m}^{DS} = (1 - q) & \left(w_{2,n}^{DS} - \epsilon(1 - \alpha_2)c_m - \epsilon\alpha_2 \left(c_r + \frac{c_v}{\theta} \right) - \epsilon(1 - \alpha_2)p_s - \frac{\epsilon}{\theta}\alpha_2 t_2 \right) (a - bp_{2,n}^{DS}) \\ & + q \left(w_{2,d}^{DS} - \epsilon c_m - \epsilon p_s \right) (a - bp_{2,d}^{DS}) \\ & \text{s.t.} \\ & (1 - \alpha_2) (a - bp_{2,n}^{DS}) \geq (a - bp_{2,d}^{DS}) \end{aligned} \quad (9)$$

$$\begin{aligned} \pi_{2,r}^{DS} = (1 - q) & \left(p_{2,n}^{DS} - w_{2,n}^{DS} + \frac{\epsilon}{\theta}\alpha_2 t_2 \right) (a - bp_{2,n}^{DS}) \\ & + q \left(p_{2,d}^{DS} - w_{2,d}^{DS} \right) (a - bp_{2,d}^{DS}) - \beta(\alpha_2)^2 \end{aligned} \quad (10)$$

The profit function definitions are similar to the profit functions for the dual-sourcing strategy in Case 1, except for the recycling cost. The recycling cost (c_v) is added to the first part of the manufacturer's profit function and removed from the first part of the retailer's profit function ($\pi_{2,r}^{DS}$). The c_v and t_2 are dependant to α_2 and $\frac{\epsilon}{\theta}$ unlike the Case 1. Another change in $\pi_{2,r}^{DS}$ is the change in the coefficient of t_2 from ϵ to $\frac{\epsilon}{\theta}$ due to the fact that the retailer now sends the recyclable products rather than recycled ones.

In Case 2, the collected, used products are sent to the manufacturer for recycling.

4.2.2. Sourcing from the retailer (SR)

The profit functions of the retailer and the manufacturer, as two members of the CLSC in this strategy, are shown in Eqs. (11) and (12), respectively.

$$\pi_{2,m}^{SR} = (1 - q) \left(w_{2,n}^{SR} - \epsilon \left(c_r + \frac{c_v}{\theta} \right) - \frac{\epsilon}{\theta} t_2 \right) (a - bp_{2,n}^{SR}) \quad (11)$$

$$\pi_{2,r}^{SR} = (1 - q) \left(p_{2,n}^{SR} - w_{2,n}^{SR} + \frac{\epsilon}{\theta} t_2 \right) (a - bp_{2,n}^{SR}) - \beta \quad (12)$$

As in the Case 1 SR strategy, the manufacturer's profit function in Case 2 is in one part. The two differences are the recycling cost (c_v) dependant to α_2 and $\frac{\epsilon}{\theta}$ added to the Case 2 manufacturer's profit function along with the coefficient of the t_2 which changed from ϵ to $\frac{\epsilon}{\theta}$ due to the recycler role of the manufacturer. For the Case 2 SR strategy, the retailer's profit function ($\pi_{2,r}^{SR}$) does not contain the recycling cost; this is in contrast to the Case 1 SR strategy, which included the recycling cost for the retailer. Besides the coefficient of t_2 has changed from ϵ to $\frac{\epsilon}{\theta}$ due to the fact that the retailer now sends recyclable products rather than recycled ones.

4.2.3. Sourcing from the supplier (SS)

Since the reverse channel of the retailer is not factored into this strategy, the profit functions and the optimal values of decision variables remain the same in both Case 1 and Case 2.

The profit functions of the manufacturer and the retailer are presented in Eqs. (13) and (14), respectively.

$$\pi_{2,m}^{SS} = (w_{2,d}^{SS} - \epsilon c_m - \epsilon p_s) (a - bp_{2,d}^{SS}) \quad (13)$$

$$\pi_{2,r}^{SS} = (p_{2,d}^{SS} - w_{2,d}^{SS}) (a - bp_{2,d}^{SS}) \quad (14)$$

Property 1. In a dual-sourcing strategy, when the retailer's recycling cost (c_u) is less than the manufacturer's recycling cost (c_v), the demand for a new product in Case 1 is higher than in Case2 under the non-disruption mode.

However, the situation is reversed in the case of disruption mode.

Property 1 can be proved by simplifying the prices of the new product in disruption mode, $p_{1,d}^{DS}$, and $p_{2,d}^{DS}$ and non-disruption mode, $p_{1,n}^{DS}$, and $p_{2,n}^{DS}$, in the Case 1 and Case 2 dual-sourcing strategy.

Property 2. The retailer has a higher tendency to choose the SR strategy in Case 2 when compared to Case 1 because the manufacturer's recycling cost (c_v) is greater than the retailer's recycling cost (c_u).

Comparing the critical probability of disruption in Cases 1 and 2, δ_2 has a higher value than δ_1 because of the higher manufacturer's recycling cost (c_v) when compared to the retailer's recycling cost (c_u).

4.3. The optimal decisions

The CLSC modeled in this paper is investigated under two cases; each case includes three sourcing strategies (DS, SR, and SS).

We used a well-recognized game-theoretic framework to model decision-making processes and identify the most favourable values for decision variables in the supply chain. The selection of this technique is based on its established efficacy in analyzing strategic interactions in situations of uncertainty. This makes it especially appropriate for studying the compromises between various sourcing methods when

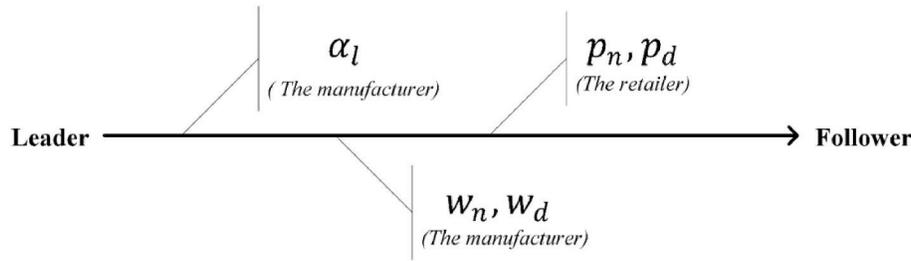


Fig. 5. The decision-making sequence.

Table 4
The optimal values of the decision variables.

Variable	Optimal values	
	Case 1	Case 2
Optimal values in DS strategy		
$P_{l,n}^{DS*}$	$\frac{b(\theta(w_{1,n}^{DS*} - \varepsilon\alpha_1^*t_1) + \varepsilon\alpha_1^*c_u) + a\theta}{2\theta b}$	$\frac{a\theta + b\theta w_{2,n}^{DS*} - b\varepsilon\alpha_2^*t_2}{2\theta b}$
$P_{l,d}^{DS*}$	$\frac{a + w_{2,d}^{DS*}b}{2b}$	$\frac{a + w_{2,d}^{DS*}b}{2b}$
$w_{l,n}^{DS*}$	$\frac{2\varepsilon b(\theta(\frac{c_r}{2} - \alpha_1^*t_1) - c_u(\alpha_1^* - \frac{1}{2})) + a\theta}{2\theta b q}$	$\frac{a\theta + \varepsilon b(\theta c_r + c_v + 2\alpha_2^*t_2)}{2\theta b}$
$w_{l,d}^{DS*}$	$\frac{\varepsilon b(\theta c_m - \theta c_r + q c_u + q\theta c_r + \theta p_s - c_u) + qa\theta}{2b\theta q}$	$\frac{\varepsilon b(c_v + \theta c_m - \theta c_r + q c_v + q\theta c_r + \theta p_s) + qa\theta}{2b\theta q}$
α_1^*	$\frac{\varepsilon b(\theta(c_r - p_s - c_m) + c_u)}{q(b\varepsilon c_u + b\varepsilon\theta c_r - \theta a)}$	$\frac{\varepsilon b(\theta(c_r - p_s - c_m) + c_v)}{q(b\varepsilon c_v + b\varepsilon\theta c_r - \theta a)}$
λ_1^*	$\frac{\varepsilon(q-1)(\theta(c_r - c_m - p_s) + c_u)}{\theta}$	$\frac{\varepsilon(q-1)(\theta(c_r - c_m - p_s) + c_v)}{\theta}$
Optimal values in SR strategy		
$P_{l,n}^{SR*}$	$\frac{a\theta + b\theta w_{1,n}^{SR*} - b\varepsilon\theta t_1 + b\varepsilon c_u}{2\theta b}$	$\frac{a\theta + b\theta w_{2,n}^{SR*} - b\varepsilon t_2}{2\theta b}$
$w_{l,n}^{SR*}$	$\frac{\varepsilon b(\theta c_r + 2\theta t_1 - c_u) + a\theta}{2b\theta}$	$\frac{\varepsilon b(\theta c_r + 2t_2 + c_v) + a\theta}{2b\theta}$
Optimal values in SS strategy		
$P_{l,d}^{SS*}$	$\frac{a + w_{2,d}^{SS*}b}{2b}$	$\frac{a + w_{2,d}^{SS*}b}{2b}$
$w_{l,d}^{SS*}$	$\frac{a + b\varepsilon c_m + b\varepsilon p_s}{2b}$	$\frac{a + b\varepsilon c_m + b\varepsilon p_s}{2b}$

confronted with disruptions in the supply chain (Kumar et al., 2018; Katsaliaki et al., 2022).

In all strategies, the manufacturer is considered the leader. The leadership of the manufacturer is widely studied in academic literature (Ranjbar et al., 2020), and companies such as Xerox (Savaskan et al., 2004) and Apple (Sahebi et al., 2015) have achieved great success with this strategy. The retailer is considered a follower who decides the retail price of new products. As depicted in Fig. 5, the games in this study are solved backwards based on game-theory principles (Aumann, 2019).

The optimal values of decision variables in each scenario for each sourcing strategy are provided in Table 4. Appendix A provides proof of all lemmas, propositions, and solving process for each optimal value.

It is clear that $\alpha_1^* = 1$ implies that the manufacturer solely relies on the reverse channel (SR), therefore, by solving $\alpha_1^* = 1$ concerning q , we gain the specific point of q , previously referred to as critical probability

of disruption (δ_l). As a result, in situations where $q \leq \delta_l$, the manufacturer prefers the SR strategy, whereas in the range of $\delta_l < q < 1$, the manufacturer prefers the dual-sourcing strategy.

5. Numerical analysis

This section begins with a numerical example to assess the proposed model's insights. A sensitivity analysis then explores the impact of managerial and organizational parameters on decision variables and functions.

5.1. Numerical example

We introduce a set of parametric values in Table 5 to illustrate a preliminary scenario and gain insights from the model. In this part, we focus on certain parameters. Specifically, we set the production cost using raw materials (c_m) to be double the cost of production using recycled materials (c_r), based on the findings of (Giri and Dey, 2019) in their study of disposable plastic cup manufacturers. Additionally, we consider the handling costs associated with recycled materials with the manufacturer (c_v) bearing the majority of this cost burden compared to the retailer (c_u)—this has been informed by previous literature (Heydari et al., 2017).

Furthermore, some of the advantages of recycling with the retailer diminish due to their higher transfer price ($t_1 = 70$) compared to the manufacturer's transfer price for recycled-product ($t_2 = 50$). In this

Table 5
The values of initial test parameters.

Parameter	Value	Parameter	Value
c_m	200	β	700
c_r	100	q	0.5
c_u	30	t_1	70
c_v	40	t_2	50
θ	0.5	p_s	90
ε	2	a	1000
b	0.5		

Table 6

Optimal results of decision variables in each Case. Case 1 is the retailer managing the recycling; Case 2 is the manufacturer managing the recycling process.

	Case 1			Case 2		
	DS	SR	SS	DS	SR	SS
$p_{l,n}^j$	1580	1580	–	1590	1590	–
$p_{l,d}^j$	1710	–	1645	1700	–	1645
$w_{l,n}^j$	1166	1180	–	1233.6	1380	–
$w_{l,d}^j$	1420	–	1290	1400	–	1290
α_i	0.31	1	0	0.27	1	0

initial scenario, we assume that 50% of the materials in a used product are recyclable (θ). This assumption is drawn from data on disposable plastic cup manufacturers used in the study by [Giri and Dey, 2019](#), indicating that the recyclability degree could exceed 50%. The likelihood of disruption (q) in the reverse supply chain is set at 50%, representing the upper end of certain ranges ([Sadjadi et al., 2018](#)); however, some simulations start with a 5% probability of disruption ([Vilko and Lättilä, 2018](#)).

Based on the initial-scenario data set from [Table 5](#), the optimal values of decision variables as well as profit functions of the manufacturer and the retailer in different case sourcing strategies, are calculated and summarized in [Tables 6 and 7](#).

5.2. Sensitivity analyses

Utilizing the initial dataset presented in [Table 5](#), we perform a sensitivity analysis to assess the impact of various managerial and organizational factors on our study’s outcomes. This analysis explores how these parameters, interacting with decision variables and operational functions, affect the study’s results.

5.2.1. Price sensitivity over ranges of the probability of disruption (q)

This section explores how fluctuating disruption probabilities (q) influence manufacturer’s wholesale prices and retailer’s retail prices in both Case 1 and Case 2. Given the unpredictable nature of disruption risks, this analysis is vital for organizations to strategically adapt their sourcing and pricing strategies. By examining a range of disruption probabilities, we aim to derive insights on optimal sourcing strategies and their effects on pricing decisions. This approach clarifies how supply chain disruptions interact with pricing strategies, which is crucial for maintaining a sustainable supply chain.

A summary of the pricing results over a range of 0–1 in q are shown in [Figs. 6 and 7](#) for Case 1 and Case 2, respectively.

As can be seen in [Figs. 6 and 7](#), the SR strategy emerges as the preferred strategy when the disruption is below 15% and 13% for Case 1 and Case 2, respectively. Notably, in both cases in SR strategy, the wholesale price ($w_{l,n}^j$) and the retail price ($p_{l,n}^j$) of the products exhibit relatively stable trends up to the critical disruption probability (δ). A noteworthy observation is the disparity in price differentials ($w_{l,n}^j$ and $p_{l,n}^j$) between Case 1 and Case 2. In Case 2, where the manufacturer bears the higher costs associated with recycling used products, there is a need to adjust the wholesale price upwards to offset these additional expenses. Consequently, in this Case, the manufacturer adjusted higher wholesale prices without significantly impacting the final retail price. Conversely, in Case 1, where the retailer does recycling, the manufacturer sets lower wholesale prices. Interestingly, from a pricing perspective, the retail price remains largely unaffected by the choice of strategy. This is exactly because of the lower wholesale price the manufacturer sets due to compensating the recycling cost of the retailer to satisfy the retailer to maintain the retail price.

The choice between Dual Sourcing (DS) and Single Sourcing (SR) strategies remains consistent across a wide range of disruption probabilities, up to approximately 95%, in Case 1 and Case 2 scenarios. Throughout this range, prices and price differences for the SR strategy

Table 7

Optimal results of profit functions in each case.

	Case 1			Case 2		
	DS	SR	SS	DS	SR	SS
$\pi_{l,m}^j$ (non disruption)	130250	158760	–	129050	144000	–
$\pi_{l,r}^j$ (non disruption)	64991	78680	–	64475	71300	–
$\pi_{l,m}^j$ (Disruption)	60900	–	126025	61500	–	126025
$\pi_{l,r}^j$ (Disruption)	20958	–	63012.5	22450	–	63012.5

A number of observations can be made from the optimal results across scenarios, modes, and strategies provided in [Appendix \(B\)](#).

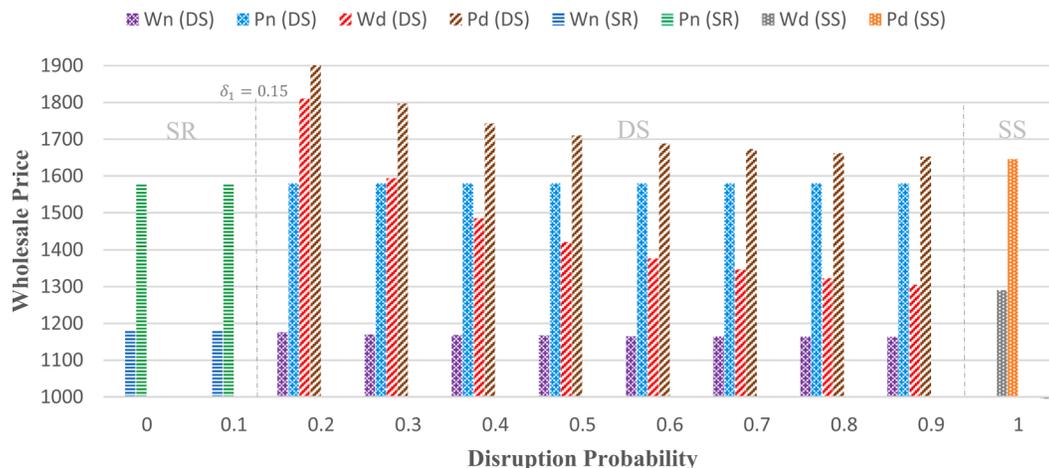


Fig. 6. The optimal pricing results for the case when recycling is completed by the retailer (Case 1) across various levels of disruption probability.

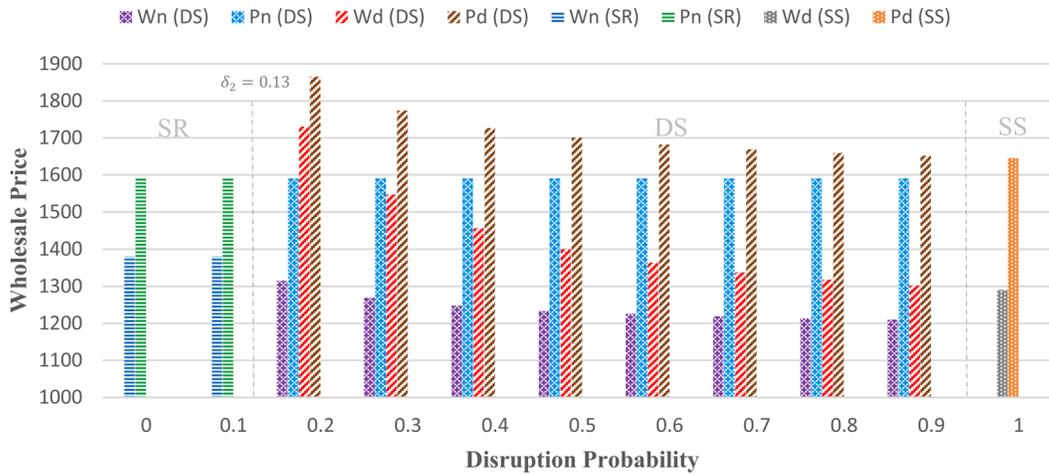


Fig. 7. The pricing results in the situation where the manufacturer has recycling capabilities (Case 2) across various levels of disruption probability.

exhibit relatively stable trends.

In Case 2 (refer to Fig. 7), there is greater sensitivity in the wholesale prices and price differentials to changes in disruption probability. As disruption probabilities increase, wholesale prices tend to decrease more rapidly. This phenomenon is primarily attributed to manufacturers recycling larger quantities and benefiting from economies of scale, allowing them to offer lower prices. Consequently, the observed decrease in wholesale prices aligns with the increasing disruption probabilities in Case 2. Manufacturers can leverage higher recycling volumes to lower their prices, ultimately maintaining competitiveness within the market.

In the DS strategy, we observe that when the value of q (disruption probability) is low, the price difference between $w_{l,d}^{DS}$ and $p_{l,d}^{DS}$ is smaller in both recycling environments—Cases 1 and 2. However, as the probability of disruption increases, the supply from the raw material supplier also increases. Consequently, the $w_{l,d}^{DS}$ falls, leading to a corresponding decline in $p_{l,d}^{DS}$ as well. As the probability of disruption increases, the difference between $w_{l,d}^{DS}$ and $p_{l,d}^{DS}$ gets larger because the drop in $w_{l,d}^{DS}$ is sharper than the drop in $p_{l,d}^{DS}$. With higher disruption probabilities, the difference between the wholesale and retail prices widens because the drop in the wholesale price is more significant than the decrease in the retail price. This trend occurs because increased supply from the raw-material supplier reduces the proportion of orders from the retailer’s reverse channel, thereby reducing the retailer’s profit. To mitigate this profit loss, the retailer aims to maintain higher prices during disruptions ($p_{l,d}^{DS}$).

As the risk (probability) of disruption increases—indicated by an increasing q —the supply from a reliable raw-material supplier with higher production cost also rises. However, it can be observed that in a non-disruption mode of the DS strategy in both cases, with increasing q , the difference between $w_{l,n}^{DS}$ and $p_{l,n}^{DS}$ surprisingly extends. The rise in q causes the manufacturer to allocate more resources to raw materials and decrease orders from the reverse channel of the retailer. Consequently, the manufacturer lowers $w_{l,n}^{DS}$ to offset retailer’s profit loss and maintain demand. As depicted in Figs. 6 and 7, this adjustment proves effective, enabling the manufacturer to persuade the retailer to maintain $p_{l,n}^{DS}$ at a constant level in the DS strategy mode.

In the SS strategy in both cases, the difference between $w_{l,d}^{SS}$ and $p_{l,d}^{SS}$ is at its largest. The reason is explained in the disruption mode of the DS strategy: the manufacturer allocates more resources to sourcing raw materials rather than utilizing recycled materials from the retailer.

The study by Gupta and Ivanov (2020) supports our findings by showing that dual sourcing can lower disruption risks. Their analysis

Table 8
Split of the order from retailer and profit levels in Case 1.

Case 1		H	α	M	L
q	H	0.2	α_1	0.23	0.26
	M	0.3		0.34	0.4
	L	0.61		0.7	0.8
Case 1		H	α	M	L
q	H	126,736	π_m	93,000	65,736
	M	130,291		97,291	69,291
	L	141,000		108,000	80,000
Case 1		H	α	M	L
q	H	63,819	π_r	46,831	32,819
	M	65,080		48,562	34,535
	L	70,216		53,643	39,535

Table 9
Order sourcing percentage from retailer and profit levels in Case 2.

Case 2		H	α	M	L
q	H	0.12	α_2	0.14	0.16
	M	0.19		0.21	0.25
	L	0.37		0.43	0.5
Case 2		H	α	M	L
q	H	126,250	π_m	93,250	65,250
	M	127,375		94,375	66,375
	L	130,750		97,750	69,750
Case 2		H	α	M	L
q	H	63,114	π_r	46,611	32,605
	M	63,663		47,155	33,144
	L	65,276		48,746	34,700

highlights the benefits of flexible sourcing strategies in response to disruption probabilities. They found that risk-averse suppliers, who offer lower wholesale prices, help manufacturers increase profits. This suggests that outsourcing recycling to retailers, similar to the approach explored in Case 2, can be an effective way to keep demand high and reduce disruption risks, aligning with Gupta and Ivanov’s (2020) work.

5.2.2. Market potential (a), split of order (α_l), and profitability ($\pi_{lm/r}^j$)

This analysis investigates how market potential (a) and disruption probability (q) influence sourcing strategies and profitability for retailers and manufacturers. It examines how orders are divided (α_l) between raw material suppliers and retailers and evaluates expected profits across different market potentials (high (H), medium (M), and low (L)) and disruption probabilities (high (H), medium (M), and low (L)). This approach sheds light on the relationship between market size, disruption risk, and their effects on sourcing choices and profitability within a sustainable supply chain framework.

The results of these analyses for Case 1 and Case 2 appear in Tables 8 and 9, respectively.

The analysis shows that in both cases, regardless of the value of q , the manufacturer tends to increase its supply from the retailer's reverse channel when the market potential (a) decreases. This strategy allows the manufacturer to maximize profit by sourcing from the channel with lower production costs, particularly in smaller markets where product pricing can be more competitive. Consequently, at the lowest values of q and a , the manufacturer relies most heavily on the retailer's reverse channel. Conversely, as q and a increase, the preference shifts towards the raw-material supplier. The findings by (Kumar et al., 2018) reinforce our observations, demonstrating how market potential, cost advantages, and disruption risks significantly influence retailers' sourcing strategies. In scenarios of low market demand, retailers often opt for lower-cost, higher-risk suppliers, mirroring our strategy of increasing reliance on reverse channel supply under such conditions. Conversely, when market growth is likely or the risk of disruption is high, retailers and manufacturers prefer more dependable suppliers. This preference for reliability in the face of potential market expansion or significant disruptions confirms the patterns we've identified, highlighting the strategic shift towards more secure sourcing options as market potential increases or disruption risks escalate.

At the lowest values of q and a , the supply from risky channels—with a lower cost of production—has the highest percentage. This scenario yields high profitability for both the manufacturer and the retailer. Peak profits are observed when q is at its lowest and a is at its highest; for instance, according to Tables 8 and in the case where the retailer manages recycling, the manufacturer's profit reaches 141,000 when $q = L$ and $a = H$. This outcome aligns with intuition, as higher market potential (larger market) corresponds to more customers, while lower disruption probability allows the manufacturer to source more from the riskier, yet cheaper, supplier, enabling them to offer the product at a more competitive price. Larger markets with low disruption risk in

recycling channels tend to favour sourcing from more sustainable sources. Therefore, opting for retailer-managed recycling, as in Case 1, is financially advantageous in such scenarios.

In both cases, an increase in q at any value of a leads to a significant drop in α_l , indicating a shift towards more secure raw-material sourcing in response to higher disruption risk. Conversely, an increase in a minimally affects the decrease in α_l , suggesting that changes in q have a greater impact on α_l than changes in market size a .

Comparing the two recycling options (Case 1 vs. Case 2), it is evident that α_l is consistently higher in Case 1 across all values of q and a . This indicates that both the manufacturer and the retailer achieve greater profitability in Case 1, where the retailer supplies recycled products at a lower price, than in Case 2, where the manufacturer handles recycling. Furthermore, Case 1 exhibits greater sensitivity to changes in a and q .

Another pattern that emerges when comparing Case 1 and 2 shows that by increasing q (regardless of a), the Case 1 manufacturer and retail profits converge with the Case 2 manufacturer and retailer profits. For example, at $q = L$ and $a = H$ for Case 1, the manufacturer profit is 141,000; the same cell in Case 2 is 130,750, a difference of 10,250. For the cell $q = H$ and $a = H$, an increase in the probability of disruption, the profit difference is reduced to 486. This happens because at higher q , the manufacturer supplies more from a reliable supplier, regardless of who is doing the recycling (Case 1 and 2).

5.2.3. Evaluation of the retailer's investment in collecting used products (I), the recyclability degree (θ), and the probability of disruption (q)

In this analyze we will conduct a sensitivity analysis focusing on investments in collection systems (I) and recyclability degrees (θ). Specifically, we will investigate how changes in the recyclability degree (θ) and the probability of disruption (q) affect the retailer's investment in used product collection (I) within the DS strategy for both Case 1 and Case 2 scenarios. The overarching insights from this analysis are summarized in Fig. 8. It's important to note that the investment function (I) is not directly dependent on θ and q . Instead, it includes the α_l . However, there exists a direct relationship between θ and q with the optimal value of α_l , resulting in an indirect relationship between (I) and both θ and q , as outlined in Eq. (1).

The analysis aims to undrestand the interrelationships among the above factors and their combined impact on the supply chain, particularly with regards to recycling practices and the management of disruptions. The purpose of this part is to provide guidance on the most effective approaches to handle reverse logistics and ensure the supply chain's resilience in the event of any disruptions.

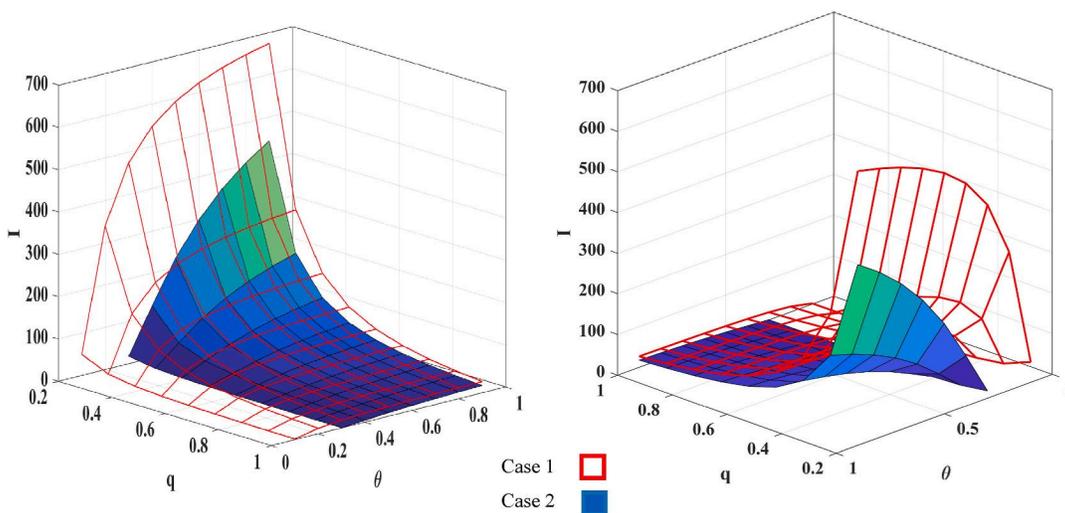


Fig. 8. The relationships between disruption probability (q), recyclability of materials (θ), and investment in the collection of used products (I), for the dual-sourcing strategy (DS).

Fig. 8 shows that in both recycling scenario cases when materials recyclability (θ) falls and the value of q increases, the retailer invests less in collecting used products. This happens for two reasons: 1) when θ is low, the retailer needs to spend more on collecting used products to arrive at the same volume of recyclable materials. This greater collection volume means higher recycling costs—locating, transportation, storage, and management become more complex. The study by Jafari et al. (2017) supports this observation, showing that as the recyclability of waste decreases, collecting and recycling waste becomes less economically beneficial for stores, leading to reduced investment in waste collection efforts.

2) A higher disruption probability means the manufacturer will likely supply more from a reliable supplier and decrease orders from the retailer. This aligns with a study by Rajabzadeh et al., 2021, which found that retailers impacted by disruptions tend to rely more heavily on dependable suppliers. This finding supports our observation that higher disruption probabilities influence manufacturers to source less from the retailer’s reverse channel, potentially due to concerns about the reliability of used product collection during disruptions.

The highest investment (I) in collecting used products is observed when the probability of disruption is at its lowest and material recyclability is at the highest proportion. This situation is ideal for the retailer for two key reasons: Firstly, with low q , the retailer experiences heightened demand from the manufacturer; secondly, the increased recyclability of materials (θ) reduces costs associated with collection and recycling.

Comparing Case 1 and Case 2 reveals that at higher values of q and increasing θ , the investment (I) remains almost constant in both scenarios. However, at lower values of q and increasing θ , there is a noticeable spike in (I), particularly pronounced in Case 1 compared to Case 2. This disparity arises from the differing recycling costs between the two cases. With a rise in θ , Case 1 sees reduced recycling costs, incentivizing the retailer to invest more in collecting used products to cut costs and boost profits. Notably, the retailer doesn’t invest in collecting used products across all θ values; there exists a minimum θ requirement for collection. This minimum θ is approximately 0.1 in Case 1, whereas in Case 2, it’s higher at around 0.3, regardless of q values. The rationale behind this discrepancy lies in the absence of recycling by the retailer in Case 2, necessitating the collection of used products for recycling by the manufacturer at a lower price than in Case 1. Consequently, the retailer prioritizes collecting used products with higher θ to maximize their value.

5.2.4. Relationships between the amount of raw materials needed to produce a unit of new product (ϵ), and consumer demand (D)

Depending on how they are designed, new products may have differing requirements for raw content; this is a parameter we have investigated in this study. We examine how increasing the amount of

raw material required (ϵ), reflecting supplier stability, affects customer demand (D) for a new product across all strategies and both cases. The relationship between D and ϵ is indirect. However, demand is linearly correlated with the retailer price (see Eq. (2)). Moreover, optimal retail prices in Case 1 and Case 2 do have a direct relationship with ϵ . These optimal equations trace an indirect relationship between demand and ϵ . In other words, the demand for a new product is negatively affected by the ϵ . As ϵ increase, the cost of collection, recycling, and transferring also increases. This leads to the manufacturer raising their wholesale prices for the product, resulting in an increase in retail prices and a decrease in demand for the new product.

The primary objective here is to understand how supplier stability, indicated by reliance on raw materials needed to produce a unit of new product, impacts the economic and operational aspects of supply chain management.

The resulting relationships across various strategies and disruption or non-disruption environments are summarized in Fig. 9 for Case 1 (the retailer recycles) and Fig. 10 for Case 2 (the manufacturer recycles).

Figs. 9 and 10 show that for each strategy (SR, DS, or SS) in both recycling operations cases, an increase in ϵ results in a decrease in D . This situation occurs because larger ϵ for retailer lead to greater used product collection, recycling, and transferring costs. These greater costs result in the manufacturer raising their wholesale prices for a product. Higher wholesale prices increases product retail prices. Greater product retail prices lead to a drop in D . This result aligns with findings in a paper by (Jafari et al., 2017), which similarly explores the dynamics of recycling requirements and their impact on supply chain pricing and demand.

The DS sourcing strategy has a critical parameter, ϵ (epsilon), which applies to both disruption and non-disruption scenarios. The critical ϵ in disruption mode and the critical ϵ in non-disruption mode are not the same in either Case 1 or Case 2. For example, in the DS strategy of Case 2 (Fig. 10), the critical ϵ in non-disruption mode is 10, and in disruption mode is approximately 5. As we see in both Figs. 9 and 10, that means in a disruptive environment, the shift in strategy from a DS to an SS strategy may not fall within the $\delta < q < 1$ range, but will shift to an SS strategy at the critical ϵ (both recycling cases are $\epsilon \approx 5$ in Figs. 9 and 10). In other words, the results show that choosing the sourcing strategy is not only dependent on q ; the values of ϵ can affect the sourcing strategy as well.

The discrepancy in critical ϵ values between disruption and non-disruption modes stems from the differing product prices. In non-disruption scenarios, the product’s price is lower compared to disruption scenarios, leading to higher demand (as evidenced in Table 6). Increasing ϵ results in higher retail prices, subsequently reducing demand. This price disparity causes demand in non-disruption mode to diminish later than in disruption mode. For a DS strategy, particularly in disruption mode, manufacturer must pay attention to critical ϵ values

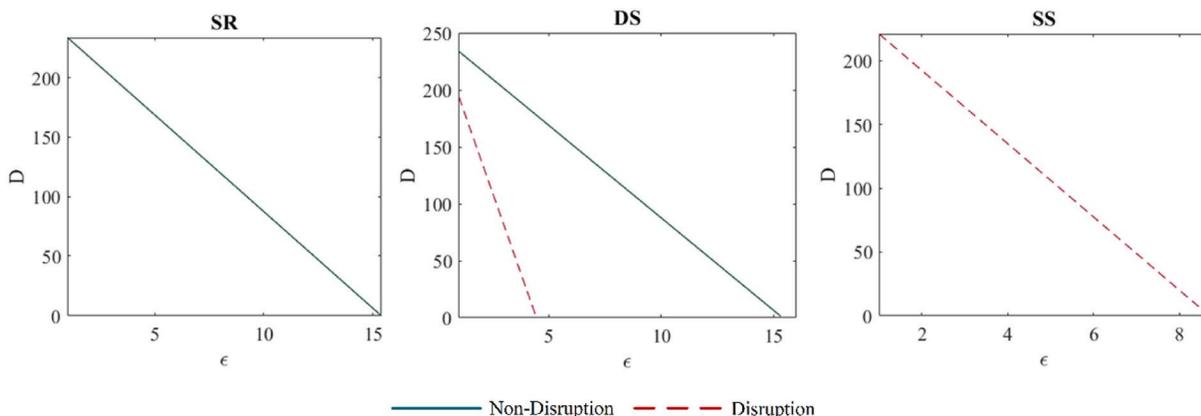


Fig. 9. Effect of changes in quantity of recycled material needed to produce a new product (ϵ) on demand (D) in Case 1, when the retailer recycles.

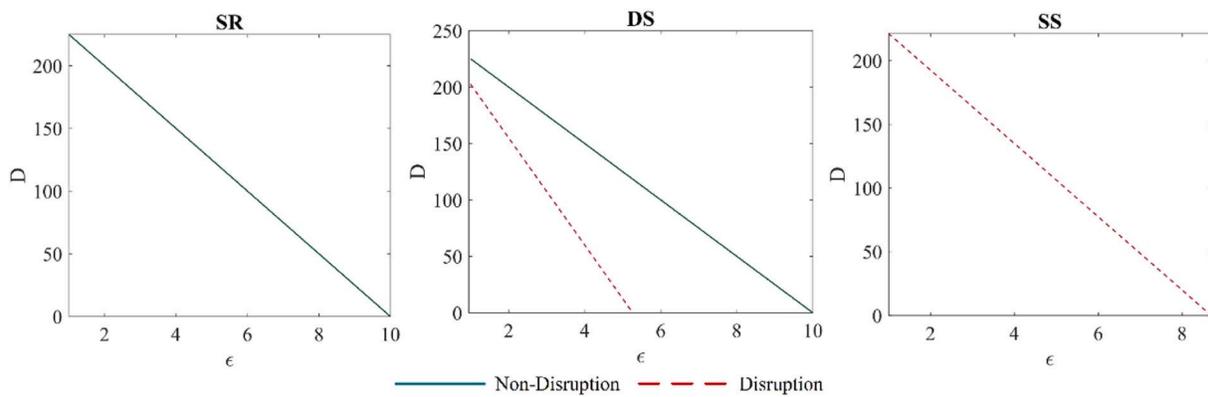


Fig. 10. Effect of changes in quantity of recycled material needed to produce a new product (ϵ) on demand (D) in Case 2, when the manufacturer recycles.

(and design products accordingly based on raw material needs), particularly in disruption mode: if a disruption occurs, ϵ should be kept below 5 in both cases to ensure profitability for the DS strategy.

Hence, if the manufacturer determines that the critical ϵ value for the DS strategy in the disruption environment falls within a specific range (above 5 and below 9, in our case), opting for an SS strategy becomes more profitable for the manufacturer than choosing a DS strategy (irrespective of the probability of disruption, q). This strategic analysis suggests that the SS strategy is not only advantageous when $q = 1$; rather, it can be the optimal choice when the ϵ value lies between the critical ϵ values of the disruption mode of DS and the critical ϵ of the SS strategy.

Considering ϵ as a measure of supplier stability indicates that sourcing strategies are influenced not only by disruption probability but also significantly by supplier reliability. This perspective aligns with the work of Cajal-Grossi et al., 2023, who empirically explored how organizations adjust sourcing strategies in response to supply chain disruptions. Their study underscores the critical role of supplier stability. They found that disruptions prompt companies to re-evaluate and often change their supplier relationships, thus emphasizing the importance of stable suppliers in strategic sourcing decisions.

Moreover, the main difference between the two cases is the critical ϵ value. The critical ϵ value in Case 1 is higher than in Case 2 except for the SS strategy; in the SS strategy, no difference exists between cases. This result is due to the lower prices in the SR and DS strategies of Case 1 compared to Case 2, each leading to higher demand for new products in Case 1 than in Case 2.

6. Discussion and managerial insights

The game-theoretic evaluation of the outsourcing of recycling in a joint forward and reverse logistics supply chain provides significant room for investigation. The investigation also considers an important dimension of supply chains and sustainability: disruption in the supply chain. The implications range from early design of products for recycling to the types of investments needed for improving collection—especially related to the collection of end-of-life products. The model proposed in this study had four major situational dimensions and a number of decision factors (see Fig. 6), which are reviewed in the next paragraph.

The decision environment begins with the basic foundation of whether a retailer (who collects end-of-life products or materials) or the manufacturer completes the recycling. In each case, the manufacturer requires material for new products. The decision that faces the manufacturer (and the supply chain in general) is whether the manufacturer completes the recycling or whether they outsource it to the retailer. The decision environment involves a crucial choice: whether a retailer or a manufacturer carries out recycling. The decision significantly impacts the whole structure of the supply chain, influencing the movement of

materials, pricing tactics, and, ultimately, the sustainability consequences, as shown in analyses. For instance, major retailers like Walmart (2024) and Tesco (James Bull, 2021) have adopted significant recycling responsibilities, influencing their suppliers and manufacturers to adhere to sustainability standards that align with the retailers' recycling capabilities and goals. This practice highlights the practical use of our model's strategic framework, showcasing its importance in the context of large-scale retail operations. After that decision is completed, another concern—whether strategic or tactical—is how much they source from the retailer who still collects end-of-life products and how much they source from a supplier of raw material. It was found that much of this part of the decision depends on the level of disruption in the return of end-of-life products. The extent of disruptions caused by returned items significantly influences the sourcing and price decisions made within the supply chain. Apple and Samsung have effectively designed recycling systems that mitigate possible disruptions by diversifying their sourcing techniques and changing prices based on the variety in the quality of recycled materials (Apple, 2023; Samsung, 2024). The methods of these companies serve as realistic case studies that demonstrate the management implications of our results. They provide a path for other enterprises to improve their resilience and profitability by implementing strategic recycling efforts. The next decision involves the wholesale prices that are set by the manufacturer and influenced by the disruptive or non-disruptive environment. Retail pricing is determined separately by the retailer, although influenced by the manufacturer's decisions and the type of disruptive environment.

There are practical and research implications for this study; we mention some major ones related to sustainability concerns, although almost every parameter or decision variable has implications. One of the major items we considered in this study is the level of investment to be made by the supply chain—whether it is the manufacturer or retailer—in helping to improve recyclability. Significant investment is required from manufacturers or retailers to improve product recyclability. Such investments not only pertain to the initial stages of product design but also extend to developing technologies that enhance the economic efficiency of recycling processes. Through an analysis of organizations such as Patagonia (ARCHANA, 2021), who have made significant financial commitments in these domains, we can see the concrete advantages of such investments in terms of cost reduction and enhanced market competitiveness. These outcomes align closely with our theoretical understanding. Two major aspects of investment can include the very beginning of the process with product design. As we have seen, the amount of recycled material required by a new product can significantly impact the pricing, profitability, and market size. If the goal is sustainability and to keep the pricing within a reasonable range so that consumers—not just green consumers—have a demand for the products, the amount of material that can be recycled and put into new products needs to be relatively larger. Investments in technology,

design, and even subsidies to improve this dimension can greatly enhance the adoption of reverse logistics across supply chains.

Another important aspect that focuses on costs in the reverse supply chain—which can also impact disruption rates—is to improve the collection system by retailers. The manufacturer’s collection system in this study under a broader ‘product stewardship’ perspective was not considered directly and explicitly, since the manufacturer relied on the recycler in this case. Research on further incentivizing the product stewardship collection system by the manufacturer for the retailer could be worthwhile in this case. This model can be extended in that direction.

The current study scenarios can be expanded to include other potential reverse logistics stages. This study focuses on collection and recycling, but many other reverse logistics and circular economy activities with sustainability and disruption implications can be further included. For example, consider the situation with a retailer collecting the material then deciding what to do with the collected material. A retailer may actually gain more value from reselling some of the material (e.g., used computers and cell phones) with no processing required. The retailer may further process remanufacturing for resale, or the retailer may provide a disassembly process and provide recycled material to the manufacturer. Each of these can be modeled with assumptions to the recycling processing costs, where reselling will require less processing than complete dismantling into fundamental materials. There are many circular economy ‘re’s’ to consider in the reverse channel. There are also additional stages of reverse logistics that may require additional stages and external entities, depending on the materials. For example, after collection, there will be sorting, disassembly, and processing activities. Some of these activities may require more capabilities than those available to the retailer. These aspects can be implicitly considered in the cost of recycling but could be made more explicit as additional intermediaries are introduced.

Another important theoretical aspect that can be investigated empirically or analytically is through consideration of transaction cost theory and cost-benefit analysis. In our model, the allocation of resources by retailers towards collection efforts is directly linked to transaction cost theory. This theory emphasizes the need to develop specialized assets for reverse logistics in order to effectively minimize supply chain costs. This is exemplified by the electronics industry, where firms like Dell have established dedicated collection systems that ensure efficient recycling and mitigate the risks associated with supply chain disruptions (Wilson and Goffnett, 2022; DELL, 2023a,b). In this situation, it is assumed that the retailer invests in collection efforts and collects used products for recycling for the manufacturer. Typically, a retailer or recovery organization will require a special investment just for the manufacturer of this product (especially in a product stewardship case). This situation strongly relates to reverse logistics supplier relationships based on building asset specificity as defined by transaction cost theory. This situation also portends the type of contractual-governance relationships and level-of-opportunism concerns. Thus, agreements could be further evaluated in this environment that may influence the profitability and pricing aspects. That is, there may be regulatory, not just competitive, forces involved that require investment by either the manufacturer or the retailer. Currently, the sustainability decisions assumed in this study are voluntary, but institutional forces may require them to become mandatory. In these cases, the model has the foundation to be expanded along these lines with some tweaking of assumptions such as subsidies provided by manufacturers to retailers to further reduce costs.

Disruption also played a number of roles in the decision process. The results demonstrated that at lower risk of disruption, both the retailer and manufacturer make higher profit when the retailer recycles as opposed to when the manufacturer recycles. This overall profitability finding can further support investments by both organizations to reduce disruption. However, this issue gets into the type of disruption. There are disruptions that can be managed—such as making sure you have multiple and incentivized sources for returned products or investments in

technology to trace products and materials. But there are also disruptions that may be beyond the control of the supply chain, such as wars and pandemics. Carefully considering the type of disruption along with probabilities is necessary and important, both practically and academically. The practical importance of our approach lies in its emphasis on disruptions that occur inside reverse logistics channels. This is particularly important in the present global supply chain environment, where disruptions are both frequent and diverse in origin. Amidst the COVID-19 pandemic, several industries, including producers of medical devices, resorted to reverse supply chains to address disruptions in conventional supply channels (Sathiya et al., 2023), which aligns with our research highlighting the need for strong reverse logistics systems. Another observation is that a high risk of disruption causes greater contrast in the pricing and profitability—contributing to greater uncertainty in the relationships that would be managed. From a perspective of relational governance, it will behoove all parties to help reduce some of these risks of disruption overall.

There will be many types of disruption relationships that exist throughout a supply chain and the reverse supply chain. We primarily focused on disruptions in the reverse supply chain (returned products) channels. There are many situations where a disruption occurs to the forward (suppliers) channel. In that case, a retailer’s recycling and reverse network can actually reduce some risk of disruption. For example, during the COVID pandemic, forward supply chains were disrupted, but some reverse supply chains covered this disruption—as in the case of ventilators and reused products locally available (e.g., see Nandi et al. (2021)).

Overall, disruption, resilience, and sustainability are interlinked to economic profitability and returns. There are many complexities and factors that require management. The concern is greater now as the circular economy, reverse logistics, regulatory policy, consumer pressures, and technological development each play a role in ultimate designs and decisions.

7. Conclusion

The current study investigates the pricing decisions in a resilient, sustainable supply chain. The raw-materials supplier, manufacturer, and retailer are investigated as supply chain members. Who does the recycling (Cases 1 and 2) and the sourcing of materials are important decisions that are investigated in this study. The tradeoff assumed is that the reverse logistics channel of the retailer may be unreliable and cause disruption compared to the raw material, which is the reliable but expensive source. A game-theoretic approach was used in a competition between the manufacturer and the retailer to investigate some of the nuances in sourcing and pricing.

These are the major results and insights.

- In a non-disruption mode, retailer recycling performs better than manufacturing recycling—implying that the manufacturer should outsource recycling to the retailer. At various levels of disruption mode, it is more profitable for the manufacturer to handle the recycling.
- In terms of the overall profit of the manufacturer and the retailer, at a lower disruption risk, retailer recycling performs better than manufacturer recycling. At higher disruption probabilities, the profit levels of the manufacturer and the retailer are almost the same.
- In both cases, at any level of disruption probability, when the market potential decreases, the manufacturer prefers to supply more from the reverse channel of the retailer to have lower production cost).
- There is a direct correlation between the recyclability degree of used products and the retailer’s incentive to collect used products.
- The sourcing strategies are not only affected by disruption probability, but the stability of the suppliers in various disruption probabilities can also affect sourcing strategies.

We identified a number of practical and research opportunities in these situations. Many of these opportunities relate to the limitations of the model and expanding the work to address assumptions such as disruption occurring only in the reverse logistics channel. There is also the assumption that recycling is handled completely by the manufacturer or completely by the retailer, without considering the division of the recycling between them.

In summary, the complexities of resilience and sustainability in supply chains unveil a broad spectrum of research opportunities. This study sheds light on critical aspects of sourcing and recycling, setting a solid foundation for enhancing supply chain resilience and sustainability. Our theoretical model has the potential to be applied to real-world situations during recent global disruptions. This framework could be tested and may be used to guide future policy formulation and strategic corporate choices. Future investigations could examine the role of product design in recyclability, assess how investments in technology and design could foster circular economy practices, and explore innovative strategies to improve collection systems. Additionally, an examination of transaction cost theory's application in reverse logistics and the regulatory landscape's impact on sustainability decisions promises valuable insights. Given the increasing disruptions in global supply chains, further research is essential to understand their effects on crucial reverse logistics phases, including sorting, disassembly, and processing.

Appendix (A). Proofs

In the game setting of DS strategy for Case 1, first, the manufacturer sets the split of the order (α_l) based on disruption risk, then sets the wholesale prices of new products (w_{li}^j). Then, the retailer sets the prices of new products (p_{li}^j). It should be noted that the wholesale prices are different in disruption mode and non-disruption mode. Consequently, the prices of the new products are also different in disruption mode and non-disruption mode.

The retailer first decides on its optimal prices by optimizing the profit function ($\pi_{1,r}^{DS}$).

Lemma 1. *In a DS strategy in Case 1, the profit function of the retailer is concave in retail prices.*

Proof: the retailer's hessian in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$ is as follows.

$$H_{\pi_{1,r}^{DS}(p_{1,n}^{DS}, p_{1,d}^{DS})} = \begin{bmatrix} \frac{\partial^2 \pi_{1,r}^{DS}}{\partial p_{1,n}^{DS 2}} & \frac{\partial^2 \pi_{1,r}^{DS}}{\partial p_{1,n}^{DS} \partial p_{1,d}^{DS}} \\ \frac{\partial^2 \pi_{1,r}^{DS}}{\partial p_{1,d}^{DS} \partial p_{1,n}^{DS}} & \frac{\partial^2 \pi_{1,r}^{DS}}{\partial p_{1,d}^{DS 2}} \end{bmatrix} = \begin{bmatrix} -2(1-q)b & 0 \\ 0 & -2qb \end{bmatrix} \quad (A.1)$$

Since $\frac{\partial^2 \pi_{1,r}^{DS}}{\partial p_{1,n}^{DS 2}} = -2(1-q)b < 0$ and $\left(\frac{\partial^2 \pi_{1,r}^{DS}}{\partial p_{1,n}^{DS} \partial p_{1,d}^{DS}}\right) - \left(\frac{\partial^2 \pi_{1,r}^{DS}}{\partial p_{1,d}^{DS} \partial p_{1,n}^{DS}}\right) = (-2(1-q)b)(-2qb) - 0 > 0$, the profit function of the retailer is concave in $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$.

Proposition 1. *The optimal values of retailer's retail prices in disruption and non-disruption modes are as Eq. (A.2) and (A.3).*

$$p_{1,n}^{DS*} = \frac{b(\theta(w_{1,n}^{DS*} - \varepsilon\alpha_1^* t_1) + \varepsilon\alpha_1^* c_u) + a\theta}{2\theta b} \quad (A.2)$$

$$p_{1,d}^{DS*} = \frac{a + w_{1,d}^{DS*} b}{2b} \quad (A.3)$$

Proof: The first derivative of retailer's profit function in DS in Case 1 ($\pi_{1,r}^{DS}$) concerning $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$ equals to:

$$\frac{\partial \pi_{1,r}^{DS}}{\partial p_{1,n}^{DS}} = (1-q)(a - bp_{1,n}^{DS}) - (1-q)\left(p_{1,n}^{DS} - w_{1,n}^{DS} + \varepsilon\alpha_1\left(b_1 - \frac{1}{\theta}c_u\right)\right)b \quad (A.4)$$

$$\frac{\partial \pi_{1,r}^{DS}}{\partial p_{1,d}^{DS}} = q\left(a - bp_{1,d}^{DS}\right) - qb\left(p_{1,d}^{DS} - w_{1,d}^{DS}\right) \quad (A.5)$$

From Eq. (A.4) and (A.5), the values of $p_{1,n}^{DS}$ and $p_{1,d}^{DS}$ are gained as Eq. (A.2) and (A.3).

Eq. (A.2) and (A.3) are substituted in the profit function of the manufacturer and its constraint.

Lemma 2. *In a DS strategy in Case 1, the profit function of the manufacturer and its constraint are concave and convex, respectively, in wholesale prices.*

Proof: the manufacturer's hessian in $w_{1,n}^{DS}$ and $w_{1,d}^{DS}$ is as follows.

This work highlights the need for pioneering solutions, including advanced technologies and sustainable practices, to strengthen supply chain resiliency amidst evolving challenges.

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CRedit authorship contribution statement

Hamed Rajabzadeh: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Meysam Rabiee:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Joseph Sarkis:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Conceptualization.

Data availability

Data will be made available on request.

$$H_{\pi_{1,m}^{DS}} \begin{pmatrix} w_{1,n}^{DS} & w_{1,d}^{DS} \end{pmatrix} = \begin{bmatrix} \frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,n}^{DS 2}} & \frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,n}^{DS} \partial w_{1,d}^{DS}} \\ \frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,d}^{DS} \partial w_{1,n}^{DS}} & \frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,d}^{DS 2}} \end{bmatrix} = \begin{bmatrix} -(1-q)b & 0 \\ 0 & -qb \end{bmatrix} \tag{A.6}$$

Since $\frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,n}^{DS 2}} = -(1-q)b < 0$ and $\left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,n}^{DS}}\right) \left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,d}^{DS}}\right) - \left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,n}^{DS} \partial w_{1,d}^{DS}}\right) \left(\frac{\partial^2 \pi_{1,m}^{DS}}{\partial w_{1,d}^{DS} \partial w_{1,n}^{DS}}\right) = (- (1-q)b)(-qb) - 0 > 0$, the profit function of the manufacturer is concave in $w_{1,n}^{DS}$ and $w_{1,d}^{DS}$.

With considering $g(w_{1,n}^{DS}, w_{1,d}^{DS}) = (1 - \alpha_1^*) \left(a - \frac{b(\theta(w_{1,n}^{DS} - \varepsilon\alpha_1^*b_1) + \varepsilon\alpha_1^*c_u) + a\theta}{2\theta} \right) \geq \left(a - \frac{a + w_{1,n}^{DS}b}{2} \right)$ it is obvious that the constraint is convex in $w_{1,n}^{DS}$ and $w_{1,d}^{DS}$.

Proposition 2. The best answers for wholesale prices and the order split in DS strategy of Case 1 are derived using Karush-Kuhn Taker (K.K.T) solutions as Eqs. (A7-9). The optimal value of the dual variable for constrain is: $\lambda_1^* = \frac{\varepsilon(q-1)(\theta(c_r - c_m - p_s) + c_u)}{0}$.

$$w_{1,n}^{DS*} = \frac{2\varepsilon b \left(\theta \left(\frac{c_r}{2} - \alpha_1^* t_1 \right) - c_u \left(\alpha_1^* - \frac{1}{2} \right) + a\theta \right)}{2\theta b q} \tag{A.7}$$

$$w_{1,d}^{DS*} = \frac{\varepsilon b (\theta c_m - \theta c_r + q c_u + q \theta c_r + \theta p_s - c_u) + q a \theta}{2b \theta q} \tag{A.8}$$

$$\alpha_1^* = \frac{\varepsilon b (\theta (c_r - p_s - c_m) + c_u)}{q (b \varepsilon c_u + b \varepsilon \theta c_r - \theta a)} \tag{A.9}$$

Proof: Putting Eq. (A.2) and (A.3) in the manufacturer's profit function ($\pi_{1,m}^{DS}$) we get

$$\begin{aligned} \pi_{1,m}^{DS} = & (1-q) \left(w_{1,n}^{DS} - \varepsilon(1-\alpha_1)c_m - \varepsilon\alpha_1 c_r - \varepsilon(1-\alpha_1)p_s - \varepsilon\alpha_1 b_1 \right) \left(a - \left(\frac{b(\theta(w_{1,n}^{DS} - \varepsilon\alpha_1 b_1) + \varepsilon\alpha_1 c_u) + a\theta}{2\theta} \right) \right) \\ & + q \left(w_{1,d}^{DS} - \varepsilon c_m - \varepsilon p_s \left(a - \left(\frac{a + w_{1,d}^{DS} b}{2} \right) \right) \right) \\ & \text{s.t} \\ & (1-\alpha_1) \left(a - \frac{b(\theta(w_{1,n}^{DS} - \varepsilon\alpha_1 b_1) + \varepsilon\alpha_1 c_u) + a\theta}{2\theta} \right) \geq \left(a - \frac{a + w_{1,n}^{DS} b}{2} \right) \end{aligned} \tag{A.10}$$

We define the function:

$$\varnothing = \pi_{1,m}^{DS} + \lambda_1 \left[(1-\alpha_1) \left(a - \frac{b(\theta(w_{1,n}^{DS} - \varepsilon\alpha_1 b_1) + \varepsilon\alpha_1 c_u) + a\theta}{2\theta} \right) \right] - \left(a - \frac{a + w_{1,n}^{DS} b}{2} \right) \tag{A.11}$$

Using KKT conditions, we get,

$$\frac{\partial \varnothing}{\partial w_{1,n}^{DS}} = (1-q) \left(a - \frac{b(\theta(w_{1,n}^{DS} - \varepsilon\alpha_1 b_1) + \varepsilon\alpha_1 c_u) + a\theta}{2\theta} \right) - \tag{A.12}$$

$$\frac{1}{2} (1-q) \left(w_{1,n}^{DS} - \varepsilon(1-\alpha_1)c_m - \varepsilon\alpha_1 c_r - \varepsilon(1-\alpha_1)p_s - \varepsilon\alpha_1 b_1 \right) b - \frac{1}{2} \lambda_1 b (1-\alpha_1)$$

$$\frac{\partial \varnothing}{\partial w_{1,d}^{DS}} = q \left(\frac{a - w_{1,d}^{DS} b}{2} \right) - \frac{q}{2} \left(w_{1,d}^{DS} - \varepsilon c_m - \varepsilon p_s \right) b + \frac{1}{2} \lambda_1 b \tag{A.13}$$

$$\begin{aligned} \frac{\partial \varnothing}{\partial \alpha_1} = & \varepsilon(1-q)(c_m - c_r - p_s - b_1) \left(a - \frac{b(\theta(w_{1,n}^{DS} - \varepsilon\alpha_1 b_1) + \varepsilon\alpha_1 c_u) + a\theta}{2\theta} \right) \\ & - \left(\frac{(1-q) \left(w_{1,n}^{DS} - \varepsilon(1-\alpha_1)c_m - \varepsilon\alpha_1 c_r - \varepsilon(1-\alpha_1)p_s - \varepsilon\alpha_1 b_1 \right) (-b\varepsilon b_1 \theta + \varepsilon b c_u)}{2\theta} \right) + \lambda_1 \left[\left(-a + \frac{b(\theta(w_{1,n}^{DS} - \varepsilon\alpha_1 b_1) + \varepsilon\alpha_1 c_u) + a\theta}{2\theta} \right) \right] - \left(\frac{(1-\alpha_1)(-b\varepsilon b_1 \theta + \varepsilon b c_u)}{2} \right) \end{aligned} \tag{A.14}$$

$$\frac{\partial \varnothing}{\partial \lambda_1} = \left[(1 - \alpha_1) \left(a - \frac{b(\theta(w_{1,n}^{DS} - \varepsilon \alpha_1 b_1) + \varepsilon \alpha_1 c_u) + a\theta)}{2\theta} \right) \right] - \frac{a}{2} + \frac{w_{1,d}^{DS} b}{2} \quad (A.15)$$

When we solve the four Eqs. (A.12-15), we get the values as Eqs. (A.7-9) and $\lambda_1^* = \frac{\varepsilon(q-1)(\theta(c_r - c_m - p_s) + c_u)}{\theta}$.

In a SR strategy in Case 1, In the game between the manufacturer and the retailer, the manufacturer decides on the wholesale price of new products ($w_{1,n}^{SR}$). Then, the retailer sets the retail price of the new products ($p_{1,n}^{SR}$).

In terms of gaining optimal values, as the follower, the retailer first sets its price.

Lemma 3. In a SR strategy in Case 1, the profit function of the retailer is concave in retail price.

Proof: the retailer's hessian in $p_{1,n}^{SR}$ is as shown in (A.16).

$$H_{\pi_{1,r}^{SR}(p_{1,n}^{SR})} = \left[\frac{\partial^2 \pi_{1,r}^{SR}}{\partial p_{1,n}^{SR} 2} \right] = [-2(1 - q)b] \quad (A.16)$$

Since $-2(1 - q)b < 0$ the profit function of the retailer is concave in $p_{1,n}^{SR}$.

Proposition 3. The optimal value of the decision variable of the retailer is as Eq. (A.17).

$$p_{1,n}^{SR*} = \frac{a\theta + b\theta w_{1,n}^{SR*} - b\varepsilon\theta t_1 + b\varepsilon c_u}{2b\theta} \quad (A.17)$$

Proof: The first derivative of retailer's profit function in SR strategy in Case 1, ($\pi_{1,r}^{SR}$) with respect to $p_{1,n}^{SR}$ equals to:

$$\frac{\partial \pi_{1,r}^{SR}}{\partial p_{1,n}^{SR}} = (1 - q) \left(a - bp_{1,n}^{SR} \right) - (1 - q) \left(p_{1,n}^{SR} - w_{1,n}^{SR} + \varepsilon \left(b_1 - \frac{1}{\theta} c_u \right) \right) b \quad (A.18)$$

From Eq. (A.18) the value of $p_{1,n}^{SR}$ is gained as Eq. (A.17).

Lemma 4. In an SR strategy in Case 1, The profit function of the manufacturer is concave wholesale price.

Proof: the manufacturer's hessian in $w_{1,n}^{SR}$ is as shown in (A.19).

$$H_{\pi_{1,m}^{SR}(w_{1,n}^{SR})} = \left[\frac{\partial^2 \pi_{1,m}^{SR}}{\partial w_{1,n}^{SR} 2} \right] = [-(1 - q)b] \quad (A.19)$$

Since $-(1 - q)b < 0$ the profit function of the manufacturer is concave in $w_{1,n}^{SR}$.

Proposition 4. In terms of maximizing the manufacturer's profit function in SR strategy of Case 1, the optimal answer for wholesale price is obtained as Eq. (A.20).

$$w_{1,n}^{SR*} = \frac{\varepsilon b(\theta c_r + 2\theta t_1 - c_u) + a\theta}{2b\theta} \quad (A.20)$$

Proof: Replacing Eq. (A.17) in the manufacturer's profit function ($\pi_{1,m}^{SR}$) we get

$$\pi_{1,m}^{SR} = (1 - q) \left(w_{1,n}^{SR} - \varepsilon c_r - \varepsilon b_1 \right) \left(a - \frac{a\theta + b\theta w_{1,n}^{SR} - b\varepsilon\theta b_1 + b\varepsilon c_u}{2\theta} \right) \quad (A.21)$$

The first derivative of manufacturer's profit function with respect to $w_{1,n}^{SR}$ is :

$$\frac{\partial \pi_{1,m}^{SR}}{\partial w_{1,n}^{SR}} = (1 - q) \left(a - \frac{a\theta + b\theta w_{1,n}^{SR} - b\varepsilon\theta b_1 + b\varepsilon c_u}{2\theta} \right) - (1 - q) \left(w_{1,n}^{SR} - \varepsilon c_r - \varepsilon b_1 \right) b \quad (A.22)$$

From Eq. (A.22) the optimal value of $w_{1,n}^{SR}$ can be gained as Eq. (A.20).

Replacing $w_{1,n}^{SR*}$ in Eq. (A.17), the $p_{1,n}^{SR*}$ can be gained.

In the SS strategy, the manufacturer, as the leader, sets the split of the order to the retailer to 0, ($\alpha_l = 0$); therefore, no collection exists. Based on the received raw materials, the manufacturer announces the wholesale price ($w_{1,d}^{SS}$) just before the retailer decides on its price ($p_{1,d}^{SS}$). Just like the previous games, the retailer announces its best price first.

Lemma 5. In a SS strategy in Case 1, the profit function of the retailer is concave in retail price.

Proof: the retailer's hessian in $p_{1,d}^{SS}$ is as follows.

$$H_{\pi_{1,r}^{SS}(p_{1,d}^{SS})} = \left[\frac{\partial^2 \pi_{1,r}^{SS}}{\partial p_{1,d}^{SS} 2} \right] = [-2b] \quad (A.23)$$

Since $-2b < 0$ the profit function of the retailer is concave in $p_{1,d}^{SS}$.

Proposition 5. The optimal retail price of new products in SS strategy of Case 1 is calculated as Eq. (A.24).

$$p_{1,d}^{SS*} = \frac{a + w_{1,d}^{SS*} b}{2b} \quad (A.24)$$

Proof: The first derivative of retailer's profit function in SS strategy in Case 1 ($\pi_{1,r}^{SS}$) with respect to $p_{1,d}^{SS}$ equals to:

$$\frac{\partial \pi_{1,r}^{SS}}{\partial p_{1,d}^{SS}} = (a - bp_{1,d}^{SS}) - (p_{1,d}^{SS} - w_{1,d}^{SS})b \tag{A.25}$$

From Eq. (A.25) the value of $p_{1,d}^{SS}$ is gained as Eq. (A.24).

Lemma 6. In a SS strategy in Case 1, the profit function of the manufacturer is concave wholesale price.

Proof: the manufacturer's hessian in $w_{1,d}^{SS}$ is as follows.

$$H_{\pi_{1,m}^{SS}}(w_{1,d}^{SS}) = \left[\frac{\partial^2 \pi_{1,m}^{SS}}{\partial w_{1,d}^{SS}{}^2} \right] = [-b] \tag{A.26}$$

Since $-b < 0$ the profit function of the manufacturer is concave in $w_{1,d}^{SS}$.

Proposition 6. The manufacturer's decision on its wholesale price in SS strategy in Case 1 is as Eq. (A.27).

$$w_{1,d}^{SS*} = \frac{a + b\epsilon c_m + b\epsilon p_s}{2b} \tag{A.27}$$

Proof: Replacing Eq. (A.24) in the manufacturer's profit function ($\pi_{1,m}^{SS}$) we get

$$\pi_{1,m}^{SS} = (w_{1,d}^{SS} - \epsilon c_m - \epsilon p_s) \left(\frac{a - w_{1,d}^{SS}b}{2} \right) \tag{A.28}$$

The first derivative of manufacturer's profit function with respect to $w_{1,d}^{SS}$ is:

$$\frac{\partial \pi_{1,m}^{SS}}{\partial w_{1,d}^{SS}} = \frac{a - w_{1,d}^{SS}b - (w_{1,d}^{SS} - \epsilon c_m - \epsilon p_s)b}{2} \tag{A.29}$$

From Eq. (A.29) the optimal value of $w_{1,d}^{SS}$ can be gained as Eq. (27).

The $p_{1,d}^{SS*}$ can be obtained by substituting the $w_{1,d}^{SS*}$ in Eq. (A.24).

Initially, in a DS strategy in Case 2, the retailer fixes its optimal prices.

Lemma 7. In a DS strategy in Case 2, the profit function of the retailer is concave in retail prices.

Proof: the retailer's hessian in $p_{2,n}^{DS}$ and $p_{2,d}^{DS}$ is as shown in (A.30).

$$H_{\pi_{2,r}^{DS}}(p_{2,n}^{DS}, p_{2,d}^{DS}) = \begin{bmatrix} \frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,n}^{DS}{}^2} & \frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,n}^{DS} \partial p_{2,d}^{DS}} \\ \frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,d}^{DS} \partial p_{2,n}^{DS}} & \frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,d}^{DS}{}^2} \end{bmatrix} = \begin{bmatrix} -2(1-q)b & 0 \\ 0 & -2qb \end{bmatrix} \tag{A.30}$$

Since $\frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,n}^{DS}{}^2} = -2(1-q)b < 0$ and $\left(\frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,n}^{DS}{}^2} \right) \left(\frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,d}^{DS}{}^2} \right) - \left(\frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,n}^{DS} \partial p_{2,d}^{DS}} \right) \left(\frac{\partial^2 \pi_{2,r}^{DS}}{\partial p_{2,d}^{DS} \partial p_{2,n}^{DS}} \right) = (-2(1-q)b)(-2qb) - 0 > 0$, the profit function of the retailer is concave in $p_{2,n}^{DS}$ and $p_{2,d}^{DS}$.

Proposition 7. The best answers of retailer's new products prices in disruption and non-disruption modes in DS strategy in Case 2 are as Eq. (A.31) and (A.32).

$$p_{2,n}^{DS*} = \frac{a\theta + b\theta w_{2,n}^{DS*} - b\epsilon \alpha_2^* t_2}{2\theta b} \tag{A.31}$$

$$p_{2,d}^{DS*} = \frac{a + w_{2,d}^{DS*}b}{2b} \tag{A.32}$$

Proof: The first derivative of retailer's profit function in DS in Case 2 ($\pi_{2,r}^{DS}$) with respect to $p_{2,n}^{DS}$ and $p_{2,d}^{DS}$ equals to:

$$\frac{\partial \pi_{2,r}^{DS}}{\partial p_{2,n}^{DS}} = (1-q) \left(a - bp_{2,n}^{DS} \right) - (1-q) \left(p_{2,n}^{DS} - w_{2,n}^{DS} + \left(\frac{\epsilon \alpha_2 b_2}{\theta} \right) \right) b \tag{A.33}$$

$$\frac{\partial \pi_{2,r}^{DS}}{\partial p_{2,d}^{DS}} = q \left(a - bp_{2,d}^{DS} \right) - qb \left(p_{2,d}^{DS} - w_{2,d}^{DS} \right) \tag{A.34}$$

From Eq. (A.33) and (A.34) the values of $p_{2,n}^{DS}$ and $p_{2,d}^{DS}$ are gained as Eq. (A.31) and (A.32).

In the next step, the values of $p_{2,n}^{DS*}$ and $p_{2,d}^{DS*}$ are substituted into the profit function of the manufacturer.

Lemma 8. In a DS strategy in Case 2 the profit function of the manufacturer and its constraint are concave and convex, respectively, in wholesale prices.

Proof: the manufacturer's hessian in $w_{2,n}^{DS}$ and $w_{2,d}^{DS}$ is as follows.

$$H_{\pi_{2,m}^{DS}}(w_{2,n}^{DS}, w_{2,d}^{DS}) = \begin{bmatrix} \frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,n}^{DS2}} & \frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,n}^{DS} \partial w_{2,d}^{DS}} \\ \frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,d}^{DS} \partial w_{2,n}^{DS}} & \frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,d}^{DS2}} \end{bmatrix} = \begin{bmatrix} -(1-q)b & 0 \\ 0 & -qb \end{bmatrix} \quad (\text{A.35})$$

Since $\frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,n}^{DS2}} = -(1-q)b < 0$ and $\left(\frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,n}^{DS}}\right)\left(\frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,n}^{DS2}}\right) - \left(\frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,n}^{DS} \partial w_{2,d}^{DS}}\right)\left(\frac{\partial^2 \pi_{2,m}^{DS}}{\partial w_{2,d}^{DS} \partial w_{2,n}^{DS}}\right) = (-(1-q)b)(-qb) - 0 > 0$, the profit function of the manufacturer is concave in $w_{2,n}^{DS}$ and $w_{2,d}^{DS}$.

With considering $g(w_{2,n}^{DS}, w_{2,d}^{DS}) = (1 - \alpha_2^*) \left(a - \frac{a\theta + b\theta w_{2,n}^{DS} - b\epsilon\alpha_2 b_2}{2\theta} \right) - \left(a - \frac{a + w_{2,n}^{DS} b}{2} \right) \geq 0$ it is obvious that the constraint is convex in $w_{2,n}^{DS}$ and $w_{2,d}^{DS}$.

Proposition 8. Using K.K.T solution, the split of the order and the wholesale prices in disruption and non-disruption modes in DS strategy in Case 2 are calculated, where $\lambda_2^* = \frac{\epsilon(q-1)(\theta(c_r - c_m - p_s) + c_v)}{\theta}$ is the optimal dual variable of the constraint.

$$w_{2,n}^{DS*} = \frac{a\theta + \epsilon b(\theta c_r + c_v + 2\alpha_2^* t_2)}{2\theta b} \quad (\text{A.36})$$

$$w_{2,d}^{DS*} = \frac{\epsilon b(c_v + \theta c_m - \theta c_r + q c_v + q \theta c_r + \theta p_s) + qa\theta}{2b\theta q} \quad (\text{A.37})$$

$$\alpha_2^* = \frac{\epsilon b(\theta(c_r - p_s - c_m) + c_v)}{q(b\epsilon c_v + b\epsilon \theta c_r - \theta a)} \quad (\text{A.38})$$

Proof: Putting Eq. (A.31) and (A.32) in the manufacturer's profit function ($\pi_{2,m}^{DS}$) we get

$$\begin{aligned} \pi_{2,m}^{DS} &= (1-q) \left(w_{2,n}^{DS} - \epsilon(1-\alpha_2)c_m - \epsilon\alpha_2 \left(c_r + \frac{c_v}{\theta} \right) - \epsilon(1-\alpha_2)p_s - \frac{\epsilon}{\theta}\alpha_2 b_2 \right) \left(a - \frac{a\theta + b\theta w_{2,n}^{DS} - b\epsilon\alpha_2 b_2}{2\theta} \right) + q \left(w_{2,d}^{DS} - \epsilon c_m - \epsilon p_s \right) \left(a - \frac{a + w_{2,d}^{DS} b}{2} \right) \\ &\quad \text{s.t.} (1-\alpha_2) \left(a - \frac{a\theta + b\theta w_{2,n}^{DS} - b\epsilon\alpha_2 b_2}{2\theta} \right) \\ &\geq \left(a - \frac{a + w_{2,n}^{DS} b}{2} \right) \end{aligned} \quad (\text{A.39})$$

We define the function:

$$\varnothing = \pi_{2,m}^{DS} + \lambda_2 \left[(1-\alpha_2) \left(a - \frac{a\theta + b\theta w_{2,n}^{DS} - b\epsilon\alpha_2 b_2}{2\theta} \right) - \left(a - \frac{a + w_{2,n}^{DS} b}{2} \right) \right] \quad (\text{A.40})$$

Using KKT conditions, we get,

$$\frac{\partial \varnothing}{\partial w_{2,n}^{DS}} = (1-q) \left(a - \frac{a\theta + b\theta w_{2,n}^{DS} - b\epsilon\alpha_2 b_2}{2\theta} \right) - \frac{1}{2} (1-q) \left(w_{2,n}^{DS} - \epsilon(1-\alpha_2)c_m - \epsilon\alpha_2 \left(c_r + \frac{c_v}{\theta} \right) - \epsilon(1-\alpha_2)p_s - \frac{\epsilon}{\theta}\alpha_2 b_2 \right) b - \frac{1}{2} \lambda_2 b (1-\alpha_2) \quad (\text{A.41})$$

$$\frac{\partial \varnothing}{\partial w_{2,d}^{DS}} = q \left(\frac{a - w_{2,d}^{DS} b}{2} \right) - \frac{q}{2} \left(w_{2,d}^{DS} - \epsilon c_m - \epsilon p_s \right) b + \frac{1}{2} \lambda_2 b \quad (\text{A.42})$$

$$\begin{aligned} \frac{\partial \varnothing}{\partial \alpha_2} &= \epsilon(1-q) \left(c_m - \left(c_r + \frac{c_v}{\theta} \right) + p_s - \frac{b_2}{\theta} \right) \left(a - \frac{a\theta + b\theta w_{2,n}^{DS} - b\epsilon\alpha_2 b_2}{2\theta} \right) + \left(\frac{(1-q) \left(w_{2,n}^{DS} - \epsilon(1-\alpha_2)c_m - \epsilon\alpha_2 \left(c_r + \frac{c_v}{\theta} \right) - \epsilon(1-\alpha_2)p_s - \frac{\epsilon}{\theta}\alpha_2 b_2 \right) \epsilon b_2 b}{2\theta} \right) \\ &\quad + \lambda_2 \left[\left(-a + \frac{a\theta + b\theta w_{2,n}^{DS} - b\epsilon\alpha_2 b_2}{2\theta} \right) + \left(\frac{(1-\alpha_1)(-b\epsilon b_2)}{2\theta} \right) \right] \end{aligned} \quad (\text{A.43})$$

$$\frac{\partial \varnothing}{\partial \lambda_2} = \left[(1-\alpha_2) \left(a + \frac{a\theta + b\theta w_{2,n}^{DS} - b\epsilon\alpha_2 b_2}{2\theta} \right) - \frac{a + w_{2,n}^{DS} b}{2} \right] \quad (\text{A.44})$$

When we solve the four Eqs. (A.41-44), we get the values as Eqs. (A.36-38) and $\lambda_2^* = \frac{\epsilon(q-1)(\theta(c_r - c_m - p_s) + c_v)}{\theta}$.

In the game setting of SR strategy in Case 2, the retailer first determines its best price, since it has lower decision power than the manufacturer as the leader.

Lemma 9. In a SR strategy in Case 2, the profit function of the retailer is concave in retail price.

Proof: the retailer's hessian in $p_{2,n}^{SR}$ is as shown in (A.45).

$$H_{\pi_{2,r}(p_{2,n}^{SR})} = \begin{bmatrix} \frac{\partial^2 \pi_{2,r}^{SR}}{\partial p_{2,n}^{SR2}} \end{bmatrix} = [-2(1-q)b] \quad (\text{A.45})$$

Since $-2(1-q)b < 0$ the profit function of the retailer is concave in $p_{2,n}^{SR}$.

Proposition 9. The optimal value of the price of new product's retail price in SR strategy of Case 2 is derived as Eq. (A.46).

$$p_{2,n}^{SR*} = \frac{a\theta + b\theta w_{2,n}^{SR} - b\epsilon t_2}{2\theta b} \tag{A.46}$$

Proof:The first derivative of retailer's profit function in SR strategy in Case 2 ($\pi_{2,r}^{SR}$) with respect to $p_{2,n}^{SR}$ equals to:

$$\frac{\partial \pi_{2,r}^{SR}}{\partial p_{2,n}^{SR}} = (1 - q) \left(a - bp_{2,n}^{SR} \right) - (1 - q) \left(p_{2,n}^{SR} - w_{2,n}^{SR} + \left(\frac{\epsilon b_1}{\theta} \right) \right) b \tag{A.47}$$

From Eq. (A.47) the value of $p_{2,n}^{SR}$ is gained as Eq. (A.46).

Lemma 10. In a SR strategy in Case 2 The profit function of the manufacturer is concave wholesale price.

Proof: the manufacturer's hessian in $w_{2,n}^{SR}$ is as shown in (A.48).

$$H_{\pi_{2,m}^{SR}(w_{2,n}^{SR})} = \left[\frac{\partial^2 \pi_{2,m}^{SR}}{\partial w_{2,n}^{SR}^2} \right] = [-(1 - q)b] \tag{A.48}$$

Since $-(1 - q)b < 0$ the profit function of the manufacturer is concave in $w_{2,n}^{SR}$.

Proposition 10. The best answer for the manufacturer's decision variable in SR strategy in Case 2 is obtained as Eq. (A.49).

$$w_{2,n}^{SR*} = \frac{\epsilon b(\theta c_r + 2t_2 + c_v) + a\theta}{2b\theta} \tag{A.49}$$

Proof: Replacing Eq. (A.46) in the manufacturer's profit function ($\pi_{2,m}^{SR}$) we get

$$\pi_{2,m}^{SR} = \pi_{2,m}^{SR} = (1 - q) \left(w_{2,n}^{SR} - \epsilon \left(c_r + \frac{c_v}{\theta} \right) - \frac{\epsilon}{\theta} b_2 \right) \left(a - \frac{a\theta + b\theta w_{2,n}^{SR} - b\epsilon b_2}{2\theta} \right) \tag{A.50}$$

The first derivative of manufacturer's profit function with respect to $w_{2,n}^{SR}$ is :

$$\frac{\partial \pi_{2,m}^{SR}}{\partial w_{2,n}^{SR}} = (1 - q) \left(a - \frac{a\theta + b\theta w_{2,n}^{SR} - b\epsilon b_2}{2\theta} \right) - \frac{1}{2} (1 - q) \left(w_{2,n}^{SR} - \epsilon c_r - \frac{\epsilon c_v}{\theta} - \frac{\epsilon b_2}{\theta} \right) b \tag{A.51}$$

From Eq. (A.51) the optimal value of $w_{2,n}^{SR}$ can be gained as Eq. (49).

Substituting $w_{2,n}^{SR*}$ in Eq. (A.46) leads to $p_{2,n}^{SR*}$.

In SS strategy, Just like the previous games, the retailer announces its best price first.

Lemma 11. In a SS strategy in Case 2, the profit function of the retailer is concave in retail price.

Proof: the retailer's hessian in $p_{2,d}^{SS}$ is as follows.

$$H_{\pi_{2,r}^{SS}(p_{2,d}^{SS})} = \left[\frac{\partial^2 \pi_{2,r}^{SS}}{\partial p_{2,d}^{SS}^2} \right] = [-2b] \tag{A.52}$$

Since $-2b < 0$ the profit function of the retailer is concave in $p_{2,n}^{SS}$.

Proposition 11. The optimal retail price of new products in SS strategy in Case 2, is calculated as Eq. (A.53).

$$p_{2,d}^{SS*} = \frac{a + w_{2,d}^{SS*} b}{2b} \tag{A.53}$$

Proof:The first derivative of retailer's profit function in SS strategy in Case 2 ($\pi_{2,r}^{SS}$) with respect to $p_{2,d}^{SS}$ equals to:

$$\frac{\partial \pi_{2,r}^{SS}}{\partial p_{2,d}^{SS}} = \left(a - bp_{2,d}^{SS} \right) - \left(p_{2,d}^{SS} - w_{2,d}^{SS} \right) b \tag{A.54}$$

From Eq. (A.54) the value of $p_{2,n}^{SR}$ is gained as Eq. (A.53).

Lemma 12. In a SS strategy in Case 2, The profit function of the manufacturer is concave wholesale price.

Proof: the manufacturer's hessian in $w_{2,d}^{SS}$ is as follows.

$$H_{\pi_{2,m}^{SS}(w_{2,d}^{SS})} = \left[\frac{\partial^2 \pi_{2,m}^{SS}}{\partial w_{2,d}^{SS}^2} \right] = [-b] \tag{A.55}$$

Since $-b < 0$ the profit function of the manufacturer is concave in $w_{2,d}^{SS}$.

Proposition 12. The manufacturer's decision on its wholesale price is as Eq. (A.56).

$$w_{2,d}^{SS*} = \frac{a + b\epsilon c_m + b\epsilon p_s}{2b} \tag{A.56}$$

Proof: Replacing Eq. (A.53) in the manufacturer's profit function ($\pi_{2,m}^{SS}$) we get

$$\pi_{2,m}^{SS} = \left(w_{2,d}^{SS} - \varepsilon c_m - \varepsilon p_s \right) \left(\frac{a - w_{2,d}^{SS} b}{2} \right) \quad (\text{A.57})$$

The first derivative of manufacturer's profit function with respect to $w_{2,d}^{SS}$ is:

$$\frac{\partial \pi_{2,m}^{SS}}{\partial w_{2,d}^{SS}} = \frac{a - w_{2,d}^{SS} b - (w_{2,d}^{SS} - \varepsilon c_m - \varepsilon p_s) b}{2} \quad (\text{A.58})$$

From Eq. (A.58) the optimal value of $w_{2,d}^{SS}$ can be gained as Eq. (A.56).

The $p_{2,d}^{SS*}$ can be obtained by substituting the $w_{1,d}^{SS*}$ in Eq. (A.53).

Property 1. In a dual sourcing strategy, since the recycling cost of the retailer (c_u) is less in comparison to the manufacturer (c_v), the demand for new products in Case 1 is higher than in Case2 for non-disruption mode. However, for the disruption mode, it is vice-versa.

Proof: The optimal prices of the new products in non-disruption mode ($p_{1,n}^{DS*}$, and $p_{2,n}^{DS*}$) in Case 1 and 2 are as follows:

$$p_{1,n}^{DS*} = \frac{\varepsilon b(c_u + \theta c_r) + 3a\theta}{4b\theta} \quad (\text{A.59})$$

$$p_{2,n}^{DS*} = \frac{\varepsilon b(c_v + \theta c_r) + 3a\theta}{4b\theta} \quad (\text{A.60})$$

Since $c_u < c_v$, therefore, $p_{1,n}^{DS*} < p_{2,n}^{DS*}$ leading to $D_1 = \alpha - p_{1,n}^{DS*} > D_2 = \alpha - p_{2,n}^{DS*}$:

The optimal prices of the new products in disruption mode ($p_{1,d}^{DS*}$, and $p_{2,d}^{DS*}$) in Case 1 and 2 are as follows:

$$p_{1,d}^{DS*} = \frac{\varepsilon b(c_u(q-1) + \theta c_m - \theta c_r + q\theta c_r + \theta p_s) + 3qa\theta}{4b\theta q} \quad (\text{A.61})$$

$$p_{2,d}^{DS*} = \frac{\varepsilon b(c_v(q-1) + \theta c_m - \theta c_r + q\theta c_r + \theta p_s) + 3qa\theta}{4b\theta q} \quad (\text{A.62})$$

Since $c_u < c_v$, and $q < 1$ therefore, $p_{2,d}^{DS*} < p_{1,d}^{DS*}$ leading to $D_1 = \alpha - p_{1,d}^{DS*} < D_2 = \alpha - p_{2,d}^{DS*}$:

Property 2. The retailer's tendency for choosing SR strategy in Case 2 is higher than in Case 1 due to the higher value of recycling cost of the manufacturer (c_v) compared to the retailer (c_u).

Proof: The critical disruption probability in Case 1 and 2 are:

$$q_1^* = \frac{\varepsilon b(\theta(c_r - c_m - p_s) + c_u)}{\varepsilon c_r b\theta - a\theta + b\varepsilon c_u} \quad (\text{A.63})$$

$$q_2^* = \frac{\varepsilon b(\theta(c_r - c_m - p_s) + c_v)}{\varepsilon c_r b\theta - a\theta + b\varepsilon c_v} \quad (\text{A.64})$$

Since $c_u < c_v$, therefore, $q_1^* < q_2^*$.

Appendix (B). Sensitivity Analysis Discussion

A number of observations can be made from the optimal results across scenarios, modes, and strategies (see Tables 5 and 6).

- The manufacturer orders more in the reverse channel from the retailer when retailers manage recycling (Case 1) in the dual sourcing (DS) strategy than in the situation where manufacturer manages the recycling (Case 2). This result contributes to the lower non-disruption manufacturer wholesale price (1166 versus 1233.6) and retailer price (1580 versus 1590) in Case 1 versus Case 2. This situation leads to both higher manufacturer (130250 versus 129050) and retailer (64991 versus 64475) profits in a non-disruption mode for Case 1 over Case 2 scenarios.
- When a disruption occurs—in contrast to the non-disruption mode—the manufacturer wholesale price (1420 versus 1400) and the retailer price (1710 versus 1700) of the DS strategy in Case 1 is greater than in Case 2. As a result, both retailer and manufacturer profitability for a DS strategy in disruption mode are less in Case 1 than in Case 2. Thus, one direct implication is if a manufacturer assumes disruption is likely occur and they adopt a dual sourcing strategy, then they should build their own recycling capacity for greater profitability.
- When the manufacturer decides on sourcing from the retailer (SR) strategy, Case 1 is the better choice since the wholesale price of the manufacturer as well as the retail price of the retailer is lower than Case 2. This makes Case 1 more profitable than Case 2 for the manufacturer and the retailer. For the single sourcing strategy disruption does not exist since the q is lower than δ making the manufacturer supply only from the reverse channel of the retailer.
- In both cases, the wholesale price of the manufacturer in a non-disruption mode in the DS strategy is lower than in the SR strategy. The reason is although, in the SR strategy, the probability of disruption is considerably lower, there is still the probability of disruption. Additionally, lacking a raw material supplier causes the manufacturer to pay a higher wholesale price in the SR strategy compared to DS strategy. Although the choice from a profitability perspective is still higher for the SR strategy.
- Overall, a goal of the whole supply chain is to reduce disruption probability and complete sourcing of recycled material from the retailer (SR strategy with profitability reaching 158760 for the manufacturer, and 78760 for the retailer). Dual sourcing in this study is the most profitable one after SR strategy. If disruption in the reverse logistics supply chain is unavoidable and consistently at a high rate, then sourcing from a raw materials supplier is the best alternative (SS strategy). Once again, a strong implication here is that uncertainty and risk of disruption in the reverse logistics supply chain needs to be managed effectively and carefully for recycling to be more profitable.

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