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Comparative study of centralized and decentralized scenarios of a three-tiered green supply chain in two-period using the game theoretical approach

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A B S T R A C T

The influence of an unorganized sector or micro-retailers in the financial system and sustainable development are becoming highly significant in several countries. Regardless of the fact that such retailers are generally reliant on wholesalers for commerce, the consequences of mediators in green supply chain management have received little attention in the existing studies. A three-tier based green supply chain(GSC) is considered in this study which consists of a manufacturer, a wholesaler and a retailer. The purpose of this investigation is to provide a decision-making structure for the identification and useful implementation of sustainable products by making comparisons of member profits, greening levels, retail prices, and ecological impact under various game structures. A two-period system is introduced to analyze the three-game strategies, especially MS, WS, and RS games. Then a two-period centralized system was implemented. The best possible feasible solution is obtained by comparing the optimal decisions in each game structure and the centralized model. The overall profit of the supply chain and the level of the greening of the products are significantly more significant in the centralized system than in any other game structure. The supply chain members could indeed make compromises on their marginal profit goals to achieve sustainable development. The results may help the supply chain members to implement more sustainability initiatives.

1. Introduction

Manufacturers frequently engage in marketing operations in the appearance of mediators to access regionally varied marketplaces or focus businesses in second or third major cities. Wholesalers or distributors are mediators who purchase directly from manufacturers and resell products to customers through retailers. Incorporating an intermediate into a distribution framework has numerous benefits. Intermediaries are always more knowledgeable about regional laws and culture, and they are often formally responsible for the product (Cole and Aitken, 2020). They also operate their distribution center or after-sales activities, execute market analysis, and arrange development programs (Soundararajan et al., 2018). By establishing procedures for both cooperation and competition throughout its supply chain, an intermediary organization can develop a learning management system that expands and sustains strongly ingrained capabilities (Lin et al., 2016). Intermediaries have been identified as essential participants who may help with the invention procedure, assist sustainability, and promote long-term entrepreneurship. Moreover, very little is recognized about the temporal dimension for improvement mediators and how they adapt over time to succeed, which would be crucial whether intermediaries are used to helping long-term sustainable improvements. In Europe, Australia, and the United States, a research approach with a systematic comparison has been adopted to evaluate four entrepreneurial intermediates at various phases of development in the associated sectors of CO2 management and carbon collection storage systems (Kant and Kanda, 2019). Marketing intermediaries are essential components of every supply chain because they transport a significant portion of manufacturing goods. Although, we have only a vague understanding of how a manufacturer should obtain the dual objectives of higher profitability and increased intermediating fulfillment. Studies must be conducted to assist manufacturers with practical solutions for improving their profitability and the contentment of their intermediaries (Sharma et al., 2020). In studies on low-carbon transformations, transition agencies that interconnect broad classes of individuals engaged in transition processes and their capabilities, resources, and perceptions become more significant. Focusing on five different incumbent transition intermediaries–Smart

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Energy GB in the United Kingdom, Energiesprong in the Netherlands, SULPHUR in Finland, CERTU in France, and the Norwegian Electric Vehicle Association and understanding their initiatives to reach socially economic objectives such as advancing initiatives or decarbonizing energy or logistics networks (Sovacool et al., 2020). In recent times, small and medium-sized enterprises (SMEs) with international activities have attracted much study attention. Another aspect of such processes is SMEs' development into international markets, which frequently depend on regional intermediaries. Such mediators keep providing valuable resources to the companies, such as business experience and recognition, while also lowering the expenses of international operations. Hence, they are often considered as strategic partners. Exploring the interaction approach as a corporate cultural component and its correlation to the trust-conflicts equilibrium is necessary to expand current understanding about the interactions between business to consumer SMEs and their mediators. According to the survey report of 165 foreign enterprise decision-makers, supplemented by in-depth discussions with 16 chief export managers, SMEs can improve effective trust whereas trying to mitigate conflict by implementing communication structures into relationship marketing (Efrat and Øyna, 2021). Eco-innovation seems to be a strategy for achieving sustainability. Although, eco-innovation can sometimes be difficult, particularly for small and medium businesses (SMEs). As a result, SMEs can consider external assistance to overcome these eco-innovation difficulties. Surveys and documentation analysis on chosen mediators in Sweden and Germany have been performed to examine such initiatives and explain the roles of wholesalers promoting eco-innovation. The results indicate that multiple types of mediators should be used in cooperation to promote eco-innovation, which policymakers should take into account (Kanda et al., 2018). Intermediaries throughout distribution networks are frequently viewed as a dying relic of less effective periods. Despite assurances that manufacturing industries would quickly "trim out the mediator" as technological innovations made logistics easier, intermediaries have thrived. The integrated result can be obtained with essential cost-based negotiations if an intermediary is involved in a framework having self-interested choice by both the manufacturer and the retailer, at which incentive mismatch causes investment and financing difficulties (Arya et al., 2015). Intermediaries are already a more significant factor of their consumers' processes in Japan (Rawwas et al., 2008). As a result, obtaining the true implications of the green supply chain (GSC) in the absence of any mediators is challenging.

Some significant issues, such as global warming, energy conservation, carbon emissions, and increasing resource depletion, have motivated many researchers to focus on ecological sustainability in the last few years. As a consequence, the worldwide community has focused on specific research & development issues (Laari et al., 2017). Already many countries' government agencies are focusing on increasing consumers' green consciousness when purchasing household appliances, office materials, and personal care products, and so on (Galitsky et al., 2004). From both the fundamental and applied standpoint, environmental sustainability is the most significant challenge. Many industrial companies have integrated sustainability trends and procedures in their supply chains (Frostenson and Prenkert, 2015). Environmental degradation associated with economic initiatives has become increasingly relevant for governments as well as financial systems in the perspective of sustainable exploration as social consciousness of such issues has increased. Environmental impacts can no longer be ignored by organizations today (Yang et al., 2011). Environmental issues, regulatory restrictions, and dynamic and challenging environmental regulations also have pushed enterprises into green supply chain management in recent times (Diabat et al., 2014). As a result, most researchers from all around the world are interested in learning more about green supply chain management (Karakayali et al., 2007). Green manufacturing becomes one of the essential components of green initiatives. It plays a significant part in improving green marketing when decision-making procedures are taken into account (Li et al., 2016). Green product manufacturing should be extended to ensure sustainable processes (Watkins et al., 2016). Green products are generally ones that have a less harmful impact upon human health as well as the ecosystem. Green manufacturing is unique because it boosts competitiveness while also benefiting the environment (Seuring, 2013). As a consequence, many industries have focused on green technologies and incorporated them into their planning processes (Ghosh and Shah, 2012).

Limited research has explored three tiered-based green supply chain operations in a multi-period framework with a wholesaler. To the best of our knowledge, this research may be the first two-period system analysis of three-tiered green supply chain management. The answers in response to related to research queries are examined throughout this study. How does a manufacturer's green procurement level increase or decrease in a supply chain? Which structure has the highest quality of products greening? Which strategy is likely to become more budget-friendly to consumers? Which process emerges to also have the maximum sales volume? Which framework has the most influence on the overall profit of a certain supply chain? How does the supply chain achieve economic and environmental success?.

The research topic in this article concerns green procurement techniques in a three-tiered supply chain in a two-period system, and it is influenced by those same examples previously presented. Industries in a supply chain collaborate to promote supply chains more efficiently and sustainably. A centralized supply chain has a single decision-maker who is constantly attempting to improve the entire system. The system is considered decentralized when each member of the same supply chain prefers to consider enhancing their structure. All members of a supply chain, in most cases, have conflicting objectives. Consequently, if one member possesses their policies, she will operate in the best way for herself instead of the entire system. This study considers a three-tiered green supply chain (GSC), including manufacturers, wholesalers, and retailers. Eco-friendly products are manufactured by a manufacturer(m) and sold to a retailer(r) via a wholesaler (w). We develop a two-period framework based on three-game strategies, namely MS, WS, and RS games. After that, we established a centralized system consisting of two periods. We compare and determine the best possible feasible solution after obtaining optimal decisions in every game structure and the centralized system.

The rest of the article is organized as follows: The related literature is reviewed concisely in Section 2. In Section 3, the model for a three-tiered green supply chain is formulated. The equilibrium outcomes in different scenarios are analyzed and compared in Section 4. In Section 5, a numerical example is used to demonstrate the best possible result in different scenarios and the sensitivity of important parameters is investigated. Conclusion, implications in reality and further research suggestions are presented in Section 6.

2. Literature review

Studies in supply chain management examined the effect of green procurement from different perspectives. For more information on the many aspects of GSC operations systems, we link to the scholarly articles to briefly explain the modeling techniques developed under price and GL-sensitive demand (Fang and Zhang, 2018; Tseng et al., 2019; Dey and Saha, 2018). Ghosh and Shah (2015) have investigated the market coordination challenges that arise from green procurement, as well as the influence of cost-sharing contracts on major decisions made by supply chain stakeholders who are pursuing green initiatives. They have shown that cost-sharing contracts throughout supply chains impact product greening degrees, pricing, and profits using a game-theoretic technique. Song and Gao (2018) have examined that the revenue-sharing contract will really help to coordinate the sharing of income across upstream and downstream participants of a sustainable supply chain even while enhancing overall effectiveness. The product's green features not only encourage more environmentally - conscious customers, but they will also have an impact on cost structure. A sequence of Stackelberg game systems is formed and analyzed to examine equilibrium decisions and revenue coordination techniques in the green supply chain, wherein two competitive retailers procure one type of eco-friendly product from a manufacturing company that considers green expenditure (Li et al., 2021). Li et al. (2016) have demonstrated that the pricing system has a significant implication on supply chain total revenues but has no effects on the product's sustainability level. Furthermore, the green level indicates the manufacturer's ecological safety level, positively connected with consumer environmental awareness, and negatively linked with the green level price factor. They have examined a dual-channel distribution network wherein the manufacturer produces green products for environmentally conscious consumers. Using the Game theoretical approach, they analyzed pricing and greening techniques for supply chain participants in both centralized and decentralized scenarios. Yenipazarli (2017) revealed that more investment in sustainable technology may not always imply economic and environmental benefits, and customer price sensitivity is really the most important element affecting manufacturers' decisions. Basiri and Heydari (2017) examined the issue of eco-friendly channel integration within a two-stage supply chain (SC). The examined SC supplies a non-green conventional product and intended to introduce substitutable sustainable products in addition to the existing conventional product. According to the study results, the collaborative effort framework is able to significantly increase SC financial gain in a manner similar to the centralized model while also ensuring higher profit margins for both supply chain participants than a decentralized structure. Jamali and Rasti-Barzoki (2018) have demonstrated how competing for the manufacturing of green products against non-green products is crucial in several markets. The retail prices of two substitute goods, an eco-friendly product manufactured by a manufacturer and a non-green product manufactured by a second manufacturer, are investigated in their study using two dual-channel distribution networks that include retail and internet sources. Compared to the decentralized scenario, the centralized scenario leads to a high green level. Except for the current study, all the mentioned articles examined the dyadic interaction between GSC participants in a two-echelon system without considering the impact of intermediates.

The optimal solution in a three-tiered GSC is investigated in this article using two different game models (Ma et al., 2019). Heydari et al. (2019) have examined the issue of optimal and integrated strategy selection for a three-tiered double sustainable supply chain. The manufacturer manufactures a product with a randomly green degree and distributes it to a wholesaler in the supply chain. When it comes to delivering products, the wholesaler has two options: selling directly to consumers or retailers. The mathematical calculations and sensitivity analysis demonstrate that their suggested method is not only financially successful for all supply chain participants, but it also improves the product's eco-friendly level and lowers prices for both the e-commerce and retail channels. In a single period system, Ding and Chen (2008) have investigated the coordination problem of a three-tiered SC selling small-life period goods. The manufacturer initially negotiates the business contract with the retailer, following with the wholesaler. They demonstrated that such a three-tiered SC would be coordinated appropriately with applicable agreements. As such the channel's total revenue may be distributed among the enterprises according to any given proportions. Inspired by the current change in global procurement and multi-channel approaches, Lan et al. (2018) have analyzed a SC in which a producer sells a product to a retailer with indeterminate demand via two wholesalers. The two wholesalers distinguish in their willingness to provide buy-back credits, and they stay competitive by offering separate wholesale prices to retailers. They demonstrated that dual structure promotes both the manufacturer as well as the retailer when the amount of demand uncertainty surpasses a specific level and that rivalry among the two wholesalers helps downstream supply chain management. Giri et al. (2016) have investigated a three-tier supply chain, including one raw material provider, one producer, and one retailer. They assumed that market demand is indeterminate and that production at raw-material suppliers and manufacturers is relevant to stochastic yield. They have shown that a composite contract composed of repurchase, sales incentive, and penalty agreements may be used to coordinate the SC. Nagaraju et al. (2018) have examined a three-echelon SC, with just a single producer providing a particular item to a single wholesaler. Then the wholesaler sells it to a single retailer. They have developed a mathematical approach for maximizing the net income of a coordinated three-tiered SC by combining ordering cost, shipping cost, and transportation cost; a mathematical approach for maximizing the net income of a coordinated three-level supply chain is developed. Due to increased concern towards the environment and corporate social responsibility over the last twenty years, closed-loop business operations have become more popular. Ranjbar et al. (2020) have considered a three-tiered closed-loop supply network that includrefed a single producer, a single retailer, and a third-party collector. Relying on game theory, they have constructed four distinct scenarios: a centralized model and three decentralized models, which are based on the Stackelberg game. They have demonstrated that the retailer leadership approach seems the most efficient and equivalent to the centralized model. In order to improve supply chain management, Aljazzar et al. (2017) have developed a variety of coordinating techniques. They have examined the integration of a three-level supply chain by combining two well-known credit terms processes which are broadly used in reality. The maximum permitted delay in payments and special offers, where the duration of the delay time and discounted rates provided across its supply network become decision variables. Zheng et al. (2019) have investigated a three-level forward and reverse supply chain that included a manufacturer, a wholesaler, and a retailer with concerns about fairness. To represent interactions between distinct parties, they used competitive and cooperative game-theoretic studies. Daryanto et al. (2019) have considered a supply chain having three-stage with carbon emission levels from the transport sector and manufacturing, as well as how to dispose of deteriorated products. The result indicates the significance of supply chain management in lowering entire supply chain expenses and lowering carbon emissions. According to the prior studies, the characteristics of a three-tiered green supply chain remain unknown in a two-period system.

Inventory control and purchasing decisions are important in the retail market (Zipkin, 2000). Hartwig et al. (2015) have studied the impacts of strategic inventory levels on supply chain management using a sequential supply chain system with two periods and price-sensitive demand. They indicated that strategic inventories possess a dual positive influence, one that is tactical and one that is behavioural, by lowering average wholesale rates and diminishing double marginalization impact. The latter effect leads to more equitable payoffs. Dey et al. (2019) have investigated the product prices, greening degree, and purchasing strategies in a manufacturer-retailer distribution network in two-period. Three rational procurement methods are taken into consideration for the price as well as greening degree sensitive demand, and associated equilibrium are examined under different game scenarios to investigate the impact of strategic inventory. The results clearly indicate how the existence of eco-friendly products influences supply chain participants' overall preferences. Moon et al. (2018) have examined a supply chain in two periods with demand determined by selling price as well as investment initiative in the involvement of strategic inventory. To determine the best pricing decisions, they have studied six strategic alternatives. This is now commonly recognized that using strategic inventory by a retailer helps reduce double marginalization and promote supply chain coordination, which may also help both the retailer and the manufacturer.

Moreover, this result is usually premised on the notion that perhaps the manufacturer may view the quantity of storage at the retailer while determining wholesale rates selections. In actuality, there are several instances where the manufacturer is unaware of the retailer's sales and inventory, successfully obscuring the retailer's activities. Roy et al. (2019) have examined the effect of a lack of visibility on the usage of strategic inventory in a distribution chain with just one retailer and one manufacturer.

Most relevantly, in all of the literature, as mentioned earlier, little consideration is given to investigating the effect of strategic inventory in a three-tiered green supply chain. They haven't really explored how strategic inventory levels influence the selling prices of supply chain participants. In conclusion, the optimal solution of a two-period purchase strategy must be investigated. This study can contribute to practitioners in recognizing pricing as well as greening level decisions in a three-tiered green supply chain with various power configurations.

3. Model Formulation

In this paper, a three-tiered based green supply chain(GSC) is considered, which consists of a manufacturer, a wholesaler, and a retailer. The three-tiered green supply chain structure is represented by the Fig. 1. A manufacturer(m) manufactures Eco - friendly products and sells products to a retailer(r) via a wholesaler(w). Considering three-game scenarios, especially MS, WS, and RS games, we develop a two-period system. Then we construct a two-period centralized system. After getting optimal decisions in each game structure and the centralized model, we compare these and try to find the best possible feasible solution. In the case of MS game, the retailer plays the role of a follower in the game between the retailer and wholesaler, and the wholesaler plays the role of a follower in the game between the wholesaler and manufacturer. Initially, the manufacturer determines the unit selling price as well as GL. After that, the wholesaler determines the wholesale price per unit. Then, the retailer determines the unit retail price and also the quantity of SI. In the case of WS game, the retailer plays the role of a follower in the game between retailer and manufacturer; the manufacturer plays the role of a follower in the game between manufacturer and wholesaler. At first, the wholesaler determines the unit wholesale price. After that, the manufacturer determines the unit selling price as well as GL. Then, the retailer determines the unit retail price and also the quantity of SI. While in the case of the RS game, the manufacturer plays the role of a follower in the game between the manufacturer and wholesaler, the wholesaler plays the role of a follower in the game between the wholesaler and retailer. Initially,the retailer determines the unit retail price and also the quantity of SI. After that, the wholesaler determines the wholesale price per unit. Then, the manufacturer determines the unit selling price as well as GL. The optimal solution is determined using backward induction methods in three games.

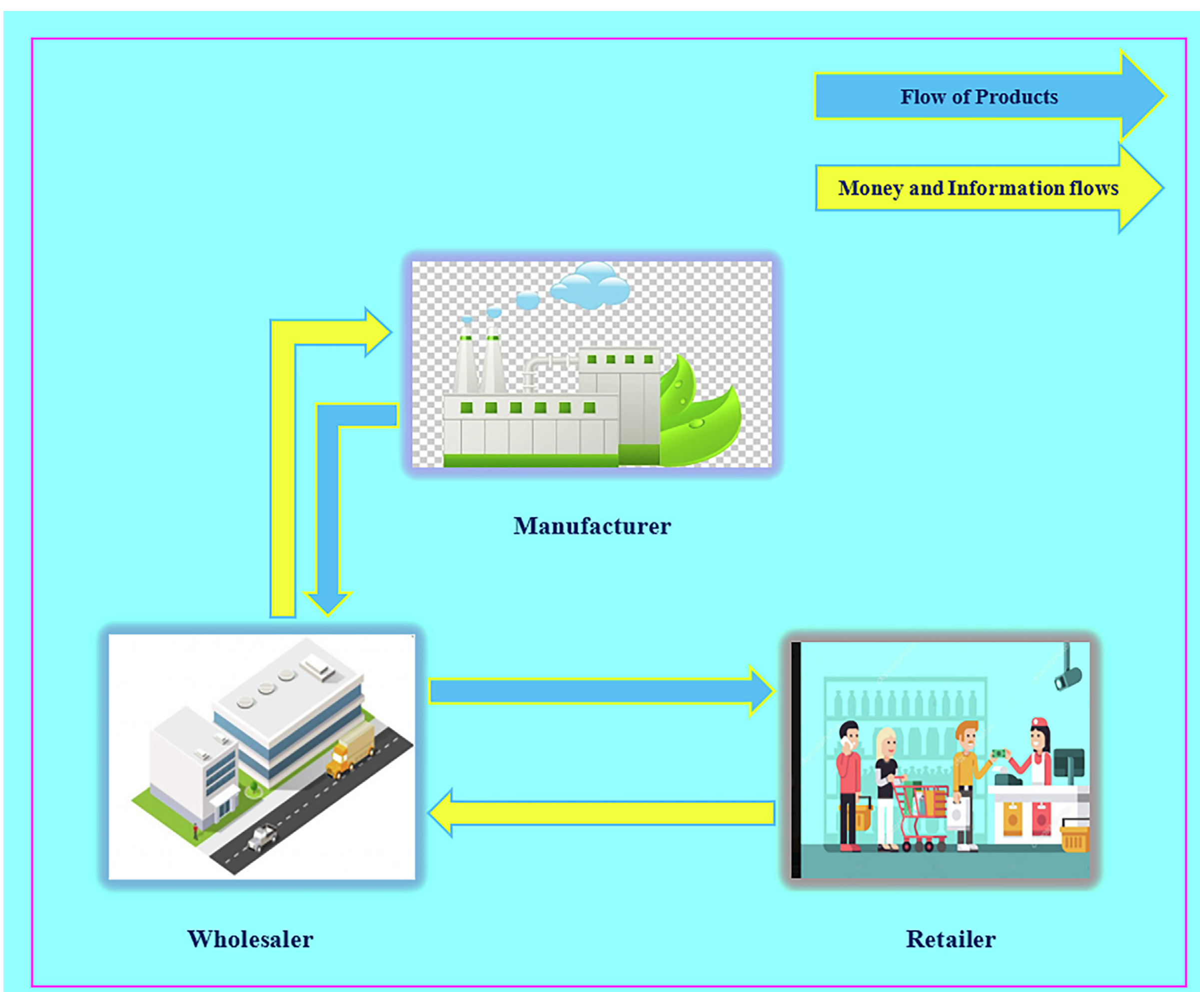

Fig. 1. Three-tiered green supply chain structure.

Table 1
Model Notation.

	Notations	Definition
Parameters	a	Total market potential
	b	Price sensitivity of consumer demand
	c	Consumer sensitivity to the greening level of products
	δ	Green investment parameter
	h	The retailer's inventory holding cost
Decision Variables	p_{irk}	The retailer's unit selling price
	p_{iwk}	The wholesaler's unit selling price
	p_{imk}	The manufacturer's unit selling price
	I_k	Volume of Strategic Inventory
	α_k	Manufacturer's greening level
Dependent Variables	D_i	Demand in the market at ith period
	Q_k	Total sales volume in two periods
	π_{2yk}	Profits of the member of the supply chain in second period, $y = m, w, r$
	π_{yk}	Profits of the member of the supply chain in two successive periods, $y = m, w, r$
	π_{sc}	Profit of the overall supply chain in two successive periods

Every new product's development includes a significant investment in market analysis to determine customer demand, the implications of technological advancements, advertisement and supervision, certification requirements, and so on. As a result, companies like Apple, Samsung, Godrej Appliances, etc. do not regularly launch new product types. Since there is a possibility that an existing product will be rejected if a new one is launched. As a result, models are designed here by considering that its GL is the same over two sequential periods (Dey et al., 2019).

Manufacturers must also consider a new development pattern that is eco-friendly rather than environmental degradation in order to ensure sustainable development. R&D activities have the potential to increase the efficiency of natural resources even by reducing negative environmental impacts (Du et al., 2019). As a consequence, green manufacturing efficiency can be improved. We have used an increasing and convex costs base to represent the costs of greening innovations. $\delta\alpha^2$ is a function of greening development and represents the costs for greening (Banker et al., 1998); where δ is the green investment parameter. The manufacturer invests in the cost for greening in each period. A lot-by-lot manufacturing strategy is maintained by the manufacturer (Ou and Feng, 2019). The lead times between the manufacturer and the wholesaler, as well as the wholesaler and the retailer, are considered to be zero. Throughout this article, we have used some notations mentioned in the Table 1.

The functional form of market demand at ith period ($i = 1,2$) and kth game scenario ($k = m, w, r, c$) are defined as

$$D_i(p_{irk}, \alpha_k) = a - bp_{irk} + c\alpha_k, i = 1, 2. \tag{1}$$

where, $a(> 0)$ is the total market potential, $b(> 0)$ is the price sensitivity of consumer demand,the consumer sensitivity to the greening level of products is c. Consumer preferences seem to be inversely related to retail price and linearly proportional to greening level.

Some of the assumptions throughout this article are given below in order to obtain the feasible solution.

(i) $a > 113bh$ and (ii) $20b\delta > 7c^2$

4. Equilibrium outcomes of game structure

Under a two-period framework, we analyze a three-tiered GSC model. Green products are manufactured and sold by the manufacturer to the wholesaler. Finally, in every period, the retailer purchases from the wholesaler and sells to the customer. The profit functions for the manufacturer, wholesaler, and retailer over two successive periods are presented below.

$$\pi_{2rk}(p_{2rk}) = (p_{2rk} - p_{2wk})D_2(p_{2rk}, \alpha_k) + p_{2wk}I_k \tag{2}$$

$$\pi_{2wk}(p_{2wk}) = (p_{2wk} - p_{2mk})(D_2(p_{2rk}, \alpha_k) - I_k) \tag{3}$$

$$\pi_{2mk}(p_{2mk}) = p_{2mk}(D_2(p_{2rk}, \alpha_k) - I_k) - \delta(\alpha_k)^2 \tag{4}$$

$$\pi_{rk}(p_{1rk}, I_k) = (p_{1rk} - p_{1wk})D_1(p_{1rk}, \alpha_k) - (p_{1wk} + h)I_k + \pi_{2rk}(p_{2rk}) \tag{5}$$

$$\pi_{wk}(p_{1wk}) = (p_{1wk} - p_{1mk})(D_1(p_{1rk}, \alpha_k) + I_k) + \pi_{2wk}(p_{2wk}) \tag{6}$$

$$\pi_{mk}(p_{1mk}, \alpha_k) = p_{1mk}(D_1(p_{1rk}, \alpha_k) + I_k) - \delta(\alpha_k)^2 + \pi_{2mk}(p_{2mk}) \tag{7}$$

4.1. Decentralized system

In a decentralized system, every supply chain participant competes to enhance their own profit. In this section, we investigate optimal decisions in three-game scenarios, namely MS, WS, and RS games.

4.1.1. MS game scenario

The manufacturer determines the unit selling price to the wholesaler and the level of greening simultaneously at the starting of the first period, i.e., p_{1mm} and α_m are determined with the expectation of wholesaler initiatives. Then with the expectation of the retailer's actions, the wholesaler determines the unit selling price to the retailer (p_{1wm}); i.e., the unit wholesale price. The retailer finally determines the unit retail price (p_{1rm}) as well as the quantity of SI (I_m) to be stocked for the next selling period. Also, at the initial stage of the second period, the manufacturer determines the unit selling price (p_{2mm}) to the wholesaler; in the second period, the manufacturer determines the same greening level (α_m) as in the first period. Then the wholesaler determines the unit wholesale price (p_{2wm}). After that, the retailer determines the unit retail price (p_{2rm}). In this scenario, the optimal solution is as follows:

$$p_{1mm} = \frac{1674376a\delta - 765760bh\delta + 29760hc^2}{3328904b\delta - 247009c^2} \tag{8}$$

$$p_{1wm} = \frac{2535180a\delta - 1167584bh\delta + 45664hc^2}{3328904b\delta - 247009c^2} \tag{9}$$

$$p_{1rm} = \frac{2932042a\delta - 583792bh\delta - 4068hc^2}{3328904b\delta - 247009c^2} \tag{10}$$

$$I_m = \frac{4b(78089a\delta - 288176bh\delta + 20121hc^2)}{3328904b\delta - 247009c^2} \tag{11}$$

$$\alpha_m = \frac{(247009a - 53800bh\delta)c}{3328904b\delta - 247009c^2} \tag{12}$$

$$p_{2mm} = \frac{248(5452a\delta + 4648bh\delta - 433hc^2)}{3328904b\delta - 247009c^2} \tag{13}$$

$$p_{2wm} = \frac{372(5452a\delta + 4648bh\delta - 433hc^2)}{3328904b\delta - 247009c^2} \tag{14}$$

$$p_{2rm} = \frac{2(1339262a\delta + 432264bh\delta - 53719hc^2)}{3328904b\delta - 247009c^2} \tag{15}$$

$$\pi_{mm} = \frac{(494018a^2 - 215200abh + 230656b^2h^2)\delta - 15376bh^2c^2}{3328904b\delta - 247009c^2} \tag{16}$$

$$\pi_{wm}=\frac{7688b\left[\begin{array}{c}(109133473a^2-50085968abh+51338880b^2h^2)\delta^2\\+hc^2(188928a-6809360bh)\delta+251105h^2c^4\end{array}\right]}{(3328904b\delta-247009c^2)^2} \tag{17}$$

$$\pi_{rm}=\frac{4b\left[\begin{array}{c}(105529463657a^2-52932887128abh+396623550976b^2h^2)\delta^2\\+hc^2(516665313a-58004491592bh)\delta+2147829266h^2c^4\end{array}\right]}{(3328904b\delta-247009c^2)^2} \tag{18}$$

$$Q_m=\frac{1047242ab\delta-280736b^2h\delta+3906bhc^2}{3328904b\delta-247009c^2} \tag{19}$$

Proof. See Appendix A.

4.1.2. WS game scenario

The wholesaler determines the unit selling price to the retailer at the starting of the first period, i.e., p_{1ww} is determined with the expectation of manufacturer initiatives. Then with the expectation of the retailer's actions, the manufacturer determines the unit selling price to the wholesaler and the level of greening simultaneously, i.e., p_{1mw} and α_w. The retailer finally determines the unit retail price (p_{1rw}) as well as the quantity of SI (I_w) to be stocked for the next selling period. Also, at the initial stage of the second period, the wholesaler determines the unit selling price (p_{2ww}) to the retailer. Then the manufacturer determines the unit selling price (p_{2mw}); in the second period, the manufacturer determines the same greening level (α_w) as in the first period. Then the retailer makes a decision on the unit retail price (p_{2rw}). In this scenario, the optimal solution is as follows:

$$p_{1mw}=\frac{(994a-464bh)\delta+16hc^2}{3844b\delta-497c^2} \tag{20}$$

$$p_{1ww}=\frac{b(1267590a-583792bh)\delta^2-c^2(111825a-43736bh)\delta+1800hc^4}{433b\delta(3844b\delta-497c^2)} \tag{21}$$

$$p_{1rw}=\frac{b(5864084a-1167584bh)\delta^2-c^2(438851a+12984bh)\delta+7064hc^4}{1732b\delta(3844b\delta-497c^2)} \tag{22}$$

$$I_w=\frac{b(624712a-2305408bh)\delta^2+c^2(23359a+265336bh)\delta-376hc^4}{1732(3844b\delta-497c^2)} \tag{23}$$

$$\alpha_w=\frac{c(497a-232bh)\delta+8hc^3}{2\delta(3844b\delta-497c^2)} \tag{24}$$

$$p_{2mw}=\frac{b(338024a+288176bh)\delta^2-c^2(29820a+45724bh)\delta+480hc^4}{433b\delta(3844b\delta-497c^2)} \tag{25}$$

$$p_{2ww}=\frac{b(1014072a+864528bh)\delta^2-c^2(89460a+137172bh)\delta+1440hc^4}{433b\delta(3844b\delta-497c^2)} \tag{26}$$

$$p_{2rw}=\frac{b(5357048a+1729056bh)\delta^2-c^2(394121a+374800bh)\delta+6344hc^4}{1732b\delta(3844b\delta-497c^2)} \tag{27}$$

$$\pi_{mw}=\frac{\begin{array}{l}b^2(419509070212a^2-192530460992abh+197346654720b^2h^2)\delta^4\\-bc^2(59626108353a^2-13514464784abh+48162047168b^2h^2)\delta^3\\+c^4(889232400a^2+1560569872abh+3382867088b^2h^2)\delta^2\\-hc^6(28627200a+57667904bh)\delta+230400h^2c^8\end{array}}{374978b\delta^2(3844b\delta-497c^2)^2} \tag{28}$$

$$\pi_{ww}=\frac{(247009a^2-107600abh+115328b^2h^2)\delta^2-hc^2(7952a+11664bh)\delta+64h^2c^4}{433\delta(3844b\delta-497c^2)} \tag{29}$$

$$\pi_{rw}=\frac{\begin{array}{l}b^2(844235709256a^2-423463097024abh+3172988407808b^2h^2)\delta^4\\-bc^2(24387185648a^2+55286172520abh+792897729472b^2h^2)\delta^3\\+c^4(1738696351a^2+5966495726abh+51629184656b^2h^2)\delta^2\\-hc^6(55974128a+89721456bh)\delta+450496h^2c^8\end{array}}{1499912b\delta^2(3844b\delta-497c^2)^2} \tag{30}$$

$$Q_w=\frac{b(523621a-140368bh)\delta^2-c^2(6958a+3510bh)\delta+112hc^4}{433\delta(3844b\delta-497c^2)} \tag{31}$$

Proof. See Appendix B.

4.1.3. RS game scenario

The retailer determines the unit retail price as well as the quantity of SI to be stocked for the next selling period at the starting of the first period, i.e., p_{1rr} and I_r are determined with the expectation of wholesaler initiatives. Then with the expectation of the manufacturer's actions, the wholesaler determines the unit selling price to the retailer, i.e., p_{1wr}. The manufacturer finally determines the unit selling price to the wholesaler and the level of greening simultaneously, i.e., p_{1mr} and α_r. Also, at the initial stage of the second period, the retailer determines the unit retail price (p_{2rr}). Then the wholesaler determines the unit selling price (p_{2wr}). After that, the manufacturer determines the unit selling price (p_{2mr}); in the second period, the manufacturer determines the same greening level (α_r) as in the first period. In this scenario, the optimal solution is as follows:

$$p_{1mr}=\frac{(128b\delta-c^2)^2[128a\delta(96b\delta+5c^2)-h(8192b^2\delta^2-576bc^2\delta+c^4)]}{4(402653184b^4\delta^4-65011712b^3c^2\delta^3+434176b^2c^4\delta^2+4224bc^6\delta-31c^8)} \tag{32}$$

$$p_{1wr}=\frac{\begin{array}{l}b^3(603979776a-402653184bh)\delta^4-b^2c^2(53477376a-51380224bh)\delta^3\\+bc^4(659456a-253952bh)\delta^2+c^6(13184a+3520bh)\delta+29hc^8\end{array}}{4(402653184b^4\delta^4-65011712b^3c^2\delta^3+434176b^2c^4\delta^2+4224bc^6\delta-31c^8)} \tag{33}$$

$$p_{1rr}=\frac{\begin{array}{l}b^3(1409286144a-402653184bh)\delta^4-b^2c^2(189792256a-47185920bh)\delta^3\\+bc^4(1724416a+827392bh)\delta^2-c^6(3328a+24896bh)\delta+123hc^8\end{array}}{4(402653184b^4\delta^4-65011712b^3c^2\delta^3+434176b^2c^4\delta^2+4224bc^6\delta-31c^8)} \tag{34}$$

$$I_r=\frac{\begin{array}{l}15bhc^8+320abc^6\delta-1536b^2hc^6\delta-114688ab^2c^4\delta^2\\-360448b^3hc^4\delta^2+7340032ab^3c^2\delta^3+41943040b^4hc^2\delta^3-268435456b^5h\delta^4\end{array}}{2(402653184b^4\delta^4-65011712b^3c^2\delta^3+434176b^2c^4\delta^2+4224bc^6\delta-31c^8)} \tag{35}$$

$$\alpha_r=\frac{c(128b\delta-c^2)\left[\begin{array}{l}a(122880b^2\delta^2+1088bc^2\delta-31c^4)\\-bh(49152b^2\delta^2-2304bc^2\delta+23c^4)\end{array}\right]}{402653184b^4\delta^4-65011712b^3c^2\delta^3+434176b^2c^4\delta^2+4224bc^6\delta-31c^8} \tag{36}$$

$$p_{2mr}=\frac{(128b\delta-c^2)\left[\begin{array}{l}48a\delta(8192b^2\delta^2-1088bc^2\delta+3c^4)\\+h(262144b^3\delta^3-45056b^2c^2\delta^2+336bc^4\delta-c^6)\end{array}\right]}{402653184b^4\delta^4-65011712b^3c^2\delta^3+434176b^2c^4\delta^2+4224bc^6\delta-31c^8} \tag{37}$$

$$p_{2wr}=\frac{\begin{array}{l}b^3(150994944a+100663296bh)\delta^4-b^2c^2(21233664a+18087936bh)\delta^3\\+bc^4(211968a+264192bh)\delta^2-c^6(432a+1392bh)\delta+3hc^8\end{array}}{402653184b^4\delta^4-65011712b^3c^2\delta^3+434176b^2c^4\delta^2+4224bc^6\delta-31c^8} \tag{38}$$

Proof. See Appendix C.

$$p_{2rr} = \frac{\begin{array}{l} b^3(704643072a + 201326592bh)\delta^4 - b^2c^2(91750400a + 42467328bh)\delta^3 \\ +bc^4(874496a + 872448bh)\delta^2 - c^6(1696a + 8032bh)\delta + 29hc^8 \end{array}}{402653184b^4\delta^4 - 65011712b^3c^2\delta^3 + 434176b^2c^4\delta^2 + 4224bc^6\delta - 31c^8} \tag{39}$$

$$\pi_{mr} = \frac{(128b\delta - c^2)^3\begin{bmatrix} 30752a^2c^8\delta - 4764729344b^5h^2c^2\delta^4 \\ +17179869184b^6h^2\delta^5 + 524288b^4\delta^3(685h^2c^4 - 7552ahc^2\delta + 73728a^2\delta^2) \\ -4096b^3c^2\delta^2(941h^2c^4 - 138496ahc^2\delta + 1683456a^2\delta^2) \\ +32b^2c^4\delta(841h^2c^4 - 119936ahc^2\delta + 8015872a^2\delta^2) \\ +b(1036288a^2c^6\delta^2 + 51520ahc^8\delta - 17h^2c^{10}) \end{bmatrix}}{16(402653184b^4\delta^4 - 65011712b^3c^2\delta^3 + 434176b^2c^4\delta^2 + 4224bc^6\delta - 31c^8)^2} \tag{40}$$

$$\pi_{wr} = \frac{b(128b\delta - c^2)^2\begin{bmatrix} 4096a^2\delta^2(1061c^8 + 23424bc^6\delta \\ +7561216b^2c^4\delta^2 - 220200960b^3c^2\delta^3 \\ +1207959552b^4\delta^4) - 256ahc^2\delta(5c^8 - 29184bc^6\delta \\ +2260992b^2c^4\delta^2 - 281018368b^3c^2\delta^3 \\ +1879048192b^4\delta^4) + h^2(c^{12} - 3456bc^{10}\delta \\ +3940352b^2c^8\delta^2 - 547356672b^3c^6\delta^3 \\ +47244640256b^4c^4\delta^4 - 618475290624b^5c^2\delta^5 \\ +2199023255552b^6\delta^6) \end{bmatrix}}{8(402653184b^4\delta^4 - 65011712b^3c^2\delta^3 + 434176b^2c^4\delta^2 + 4224bc^6\delta - 31c^8)^2} \tag{41}$$

$$\pi_{rr} = \frac{b\begin{bmatrix} h^2(128b\delta - c^2)^2(16384b^2\delta^2 - 2304bc^2\delta - 15c^4) \\ +4096a^2\delta^2(49152b^2\delta^2 - 1792bc^2\delta + 19c^4) \\ -128ahc^2\delta(114688b^2\delta^2 - 1792bc^2\delta + 5c^4) \end{bmatrix}}{4(402653184b^4\delta^4 - 65011712b^3c^2\delta^3 + 434176b^2c^4\delta^2 + 4224bc^6\delta - 31c^8)} \tag{42}$$

$$Q_r = \frac{\begin{array}{c} b(128b\delta - c^2)[64a\delta(49152b^2\delta^2 - 2176bc^2\delta - c^4) \\ -h(98304b^2c^2\delta^2 - 640bc^4\delta + 3c^6)] \end{array}}{4(402653184b^4\delta^4 - 65011712b^3c^2\delta^3 + 434176b^2c^4\delta^2 + 4224bc^6\delta - 31c^8)} \tag{43}$$

4.2. Centralized system

Every supply chain participant is integrated vertically in a centralized framework. Under this structure, a central authority with all necessary information contributes to making all effective decisions. The optimal retailer selling price, strategic inventory, wholesaler selling price, manufacturer selling price, and greening level are determined by the central authority for the entire supply chain. A centralized supply chain solves the issue of double marginalization and enables all the members to properly coordinate their respective objectives. As a consequence, all the equilibrium outcomes of a supply chain in a centralized system are optimized globally. In this system, the optimal solution is as follows:

$$p_{1mc} = \frac{8(3a - 2bh)\delta + hc^2}{8(10b\delta - c^2)} \tag{44}$$

$$p_{1wc} = \frac{8(3a - 2bh)\delta + hc^2}{4(10b\delta - c^2)} \tag{45}$$

$$p_{1rc} = \frac{2(4a - bh)\delta}{10b\delta - c^2} \tag{46}$$

$$I_c = \frac{b[8(a - 4bh)\delta + 3hc^2]}{8(10b\delta - c^2)} \tag{47}$$

$$\alpha_c = \frac{c(4a - bh)}{4(10b\delta - c^2)} \tag{48}$$

$$p_{2mc} = \frac{8(a + bh)\delta - hc^2}{4(10b\delta - c^2)} \tag{49}$$

$$p_{2wc} = \frac{8(a + bh)\delta - hc^2}{2(10b\delta - c^2)} \tag{50}$$

$$p_{2rc} = \frac{8(7a + 2bh)\delta - 3hc^2}{8(10b\delta - c^2)} \tag{51}$$

$$\pi_{mc} = \frac{64b(13a^2 - 4abh + 8b^2h^2)\delta^2 - 8c^2(16a^2 - 6abh + 13b^2h^2)\delta + 5bh^2c^4}{64(10b\delta - c^2)^2} \tag{52}$$

$$\pi_{wc} = \frac{b[64(13a^2 - 4abh + 8b^2h^2)\delta^2 - 16hc^2(a + 6bh)\delta + 5h^2c^4]}{64(10b\delta - c^2)^2} \tag{53}$$

$$\pi_{rc} = \frac{b[64(11a^2 + 2abh + 16b^2h^2)\delta^2 - 16hc^2(3a + 13bh)\delta + 11h^2c^4]}{64(10b\delta - c^2)^2} \tag{54}$$

$$Q_c = \frac{b(40a\delta - hc^2)}{8(10b\delta - c^2)} \tag{55}$$

where subscript c stands for the centralized case.

Proof. See Appendix D.

4.3. Propositions

After getting all the equilibrium outcomes in both the decentralized and centralized systems, we compared these solutions to find the best feasible solution. As a necessary consequence, we have formulated the fundamental propositions given below.

Proposition-1. The total profit of the retailer in different game structures satisfies the following conditions.

(i) $\pi_{rr} \geqslant \pi_{rw} \geqslant \pi_{rm}$
(ii) $\pi_{rc} \geqslant \pi_{rw} \geqslant \pi_{rm}$
(iii) $\pi_{rc} > \pi_{rr}$ in the region bounded by $8.79 < c \leq 15, 5 \leqslant \delta \leq 14.56$ and the curve $\Psi_1 = 0; \pi_{rc} \leqslant \pi_{rr}$ for all other values of c and δ.

Proof. See Appendix E.

Proposition-2. The total profit of the wholesaler in different game structures satisfies the following conditions.

(i) $\pi_{ww} \geqslant \pi_{wr}$ and $\pi_{wc} \geqslant \pi_{wr}$
(ii) $\pi_{ww} \geqslant \pi_{wm}$ and $\pi_{wc} \geqslant \pi_{wm}$
(iii) $\pi_{wr} > \pi_{wm}$ in the region bounded by $12.82 \leqslant c \leq 15, 5 \leqslant \delta < 6.84$ and the curve $\Psi_2 = 0; \pi_{wr} \leqslant \pi_{wm}$ for all other values of c and δ.
(iv) $\pi_{wc} > \pi_{ww}$ in the region bounded by $8.72 \leqslant c \leqslant 15, 5 \leqslant \delta \leqslant 14.82$ and the curve $\Psi_3 = 0; \pi_{wc} \leqslant \pi_{ww}$ for all other values of c and δ.

Proof. See Appendix F.

Proposition-3. The total profit of the manufacturer in different game structures satisfies the following conditions.

(i) $\pi_{mw} \geqslant \pi_{mr}$
(ii) $\pi_{mm} \geqslant \pi_{mw}$ and $\pi_{mm} \geqslant \pi_{mc}$
(iii) $\pi_{mr} > \pi_{mc}$ in the region bounded by $14.21 \leqslant c \leqslant 15, 5 \leqslant \delta \leqslant 5.57$ and the curve $\Psi_4 = 0; \pi_{mr} \leqslant \pi_{mc}$ for all other values of c and δ.
(iv) $\pi_{mw} > \pi_{mc}$ in the region bounded by $12.6 < c \leqslant 15, 5 \leqslant \delta < 7.09$ and the curve $\Psi_5 = 0; \pi_{mw} \leqslant \pi_{mc}$ for all other values of c and δ.

Proof. See Appendix G.

Proposition-4. Greening levels of the product in different game structures satisfies the following conditions.

(i) $\alpha_m \geqslant \alpha_r$ and $\alpha_w \geqslant \alpha_r$
(ii) $\alpha_c \geqslant \alpha_m$ and $\alpha_c \geqslant \alpha_w$
(iii) $\alpha_w > \alpha_m$ in the region bounded by $9.25 \leqslant c \leqslant 15, 5 \leqslant \delta < 13.15$ and the curve $\Psi_6 = 0; \alpha_w \leqslant \alpha_m$ for all other values of c and δ.

Proof. See Appendix H.

Proposition-5. Total sales volume of the product in different game structures satisfies the following conditions.

(i) $Q_w \geqslant Q_m$
(ii) $Q_r > Q_m$ in the region bounded by $11.34 \leqslant c \leqslant 15, 5 \leqslant \delta < 8.75$ and the curve $\Psi_7 = 0; Q_r \leqslant Q_m$ for all other values of c and δ.
(iii) $Q_r > Q_w$ in the region bounded by $14.46 < c \leqslant 15, 5 \leqslant \delta < 5.38$ and the curve $\Psi_8 = 0; Q_r \leqslant Q_w$ for all other values of c and δ.
(iv) $Q_c \geqslant Q_r$ and $Q_c \geqslant Q_w$

Proof. See Appendix I.

Proposition-6. The retailer's unit selling price of the product in the first period in different game structures satisfies the following conditions.

(i) $p_{1rr} \leqslant p_{1rw}$
(ii) $p_{1rw} \leqslant p_{1rm}$ and $p_{1rc} \leqslant p_{1rm}$
(iii) $p_{1rw} < p_{1rc}$ in the region bounded by $9.83 \leqslant c \leqslant 15, 5 \leqslant \delta < 11.66$ and the curve $\Psi_9 = 0; p_{1rc} \leqslant p_{1rw}$ for all other values of c and δ.
(iv) $p_{1rr} < p_{1rc}$ in the region bounded by $7.17 \leqslant c \leqslant 15, 5 \leqslant \delta < 21.9$ and the curve $\Psi_{10} = 0; p_{1rc} \leqslant p_{1rr}$ for all other values of c and δ.

Proof. See Appendix J.

Proposition-7. The retailer's unit selling price of the product in the second period in different game structures satisfies the following conditions.

(i) $p_{2rc} \leqslant p_{2rr}, p_{2rc} \leqslant p_{2rw}$, and $p_{2rc} \leqslant p_{2rm}$
(ii) $p_{2rr} < p_{2rm}$ in the region bounded by $10.55 \leqslant c \leqslant 15$ and $5 \leqslant \delta < 10.12$ and the curve $\Psi_{11} = 0; p_{2rm} \leqslant p_{2rr}$ for all other values of c and δ.
(iii) $p_{2rr} < p_{2rw}$ in the region bounded by $12.23 < c \leqslant 15$ and $5 \leqslant \delta < 7.52$ and the curve $\Psi_{12} = 0; p_{2rw} \leqslant p_{2rr}$ for all other values of c and δ.
(iv) $p_{2rm} < p_{2rw}$ in the region bounded by $12.02 \leqslant c \leqslant 15$ and $5 \leqslant \delta < 7.79$ and the curve $\Psi_{13} = 0; p_{2rw} \leqslant p_{2rm}$ for all other values of c and δ.

Proof. See Appendix K.

Proposition-8. The retailer's unit selling price of the product in different game structures satisfies the following conditions.

(i) $p_{2rm} \leqslant p_{1rm}$
(ii) $p_{2rw} \leqslant p_{1rw}$
(iii) $p_{1rr} \leqslant p_{2rr}$
(iv) $p_{2rc} \leqslant p_{1rc}$

Proof. See Appendix L.

Proposition-9. The volume of strategic inventory in different game structures satisfies the following conditions.

(i) $I_w \geqslant I_m$ and $I_c \geqslant I_m$
(ii) $I_w > I_c$ in the region bounded by $6.05 \leqslant c \leqslant 15$ and $5 \leqslant \delta < 25$ and the curve $\Psi_{14} = 0; I_w \leqslant I_c$ for all other values of c and δ.
(iii) $I_r > I_m$ in the region bounded by $14.05 < c \leqslant 15$ and $5 \leqslant \delta < 7$ and the curve $\Psi_{15} = 0; I_r \leqslant I_m$ for all other values of c and δ.
(iv) $I_r > I_c$ in the region bounded by $14.68 \leqslant c \leqslant 15$ and $5 \leqslant \delta \leqslant 5.22$ and the curve $\Psi_{16} = 0; I_r \leqslant I_c$ for all other values of c and δ.

Proof. See Appendix M.

Where,

$\Psi_1 = 432712c^{12} - 5.11031 \times 10^{10}c^{10}\delta + 5.57727 \times 10^{15}c^8\delta^2 - 5.38136 \times 10^{18}c^6\delta^3 + 1.67304 \times 10^{21}c^4\delta^4 - 7.98931 \times 10^{22}c^2\delta^5 + 8.54711 \times 10^{23}\delta^6$,

$\Psi_2 = 267839c^{20} + 9.6771 \times 10^8c^{18}\delta - 4.76295 \times 10^{15}c^{16}\delta^2 + 1.06047 \times 10^{19}c^{14}\delta^3 - 8.81209 \times 10^{21}c^{12}\delta^4 + 7.2672 \times 10^{24}c^{10}\delta^5 - 5.84908 \times 10^{27}c^8\delta^6 + 1.56976 \times 10^{30}c^6\delta^7 - 6.29371 \times 10^{31}c^4\delta^8 - 2.21773 \times 10^{33}c^2\delta^9 + 9.16809 \times 10^{34}\delta^{10}$,

$\Psi_3 = c^8 - 123736c^6\delta + 3.85909 \times 10^9c^4\delta^2 - 2.83523 \times 10^{11}c^2\delta^3 + 3.41836 \times 10^{12}\delta^4$,

$\Psi_4 = 654665c^{20} + 3.33588 \times 10^{10}c^{18}\delta - 1.68355 \times 10^{15}c^{16}\delta^2 + 8.77618 \times 10^{18}c^{14}\delta^3 - 1.5983 \times 10^{22}c^{12}\delta^4 + 1.01663 \times 10^{25}c^{10}\delta^5 + 1.23515 \times 10^{27}c^8\delta^6 - 2.97145 \times 10^{30}c^6\delta^7 + 4.41887 \times 10^{32}c^4\delta^8 - 2.26291 \times 10^{34}c^2\delta^9 + 3.84565 \times 10^{35}\delta^{10}$,

$\Psi_5 = 292648c^{12} - 3.70338 \times 10^{10}c^{10}\delta + 1.15226 \times 10^{15}c^8\delta^2 + 1.15609 \times 10^{18}c^6\delta^3 - 2.16499 \times 10^{20}c^4\delta^4 + 1.1947 \times 10^{22}c^2\delta^5 - 1.99286 \times 10^{23}\delta^6$,

$\Psi_6 = 804829c^7 - 5.01601 \times 10^{10}c^5\delta + 4.25674 \times 10^{12}c^3\delta^2 - 5.81559 \times 10^{13}c\delta^3$,

$\Psi_7 = 712331c^{10} - 3.20327 \times 10^{11}c^8\delta + 1.18608 \times 10^{15}c^6\delta^2 - 7.70341 \times 10^{17}c^4\delta^3 - 1.73889 \times 10^{20}c^2\delta^4 + 4.96107 \times 10^{21}\delta^5$,

$\Psi_8 = 245408c^{12} - 1.56926\times 10^{10}c^{10}\delta + 2.54343\times 10^{13}c^8\delta^2 - 3.17745\times 10^{16}c^6\delta^3 + 2.20383\times 10^{19}c^4\delta^4 + 2.34062\times 10^{21}c^2\delta^5 - 1.34255\times 10^{23}\delta^6,$

$\Psi_9 = 965445c^6 - 6.00754\times 10^{10}c^4\delta + 3.91724\times 10^{12}c^2\delta^2 - 5.32463\times 10^{13}\delta^3,$

$\Psi_{10} = 991935c^{10} - 3.66126\times 10^{10}c^8\delta + 1.3036\times 10^{14}c^6\delta^2 - 1.12361\times 10^{17}c^4\delta^3 + 6.06112\times 10^{18}c^2\delta^4 - 5.05636\times 10^{19}\delta^5,$

$\Psi_{11} = c^{10} - 44186.4c^8\delta + 1.51015\times 10^8c^6\delta^2 - 1.21443\times 10^{11}c^4\delta^3 + 5.82584\times 10^{12}c^2\delta^4 - 7.11528\times 10^{13}\delta^5,$

$\Psi_{12} = 817684c^{12} - 5.25974\times 10^{10}c^{10}\delta + 9.12331\times 10^{13}c^8\delta^2 - 6.97326\times 10^{16}c^6\delta^3 + 3.67615\times 10^{19}c^4\delta^4 - 2.2017\times 10^{21}c^2\delta^5 + 3.47631\times 10^{22}\delta^6,$

$\Psi_{13} = 8.67042\times 10^{11}c^6 - 5.39647\times 10^{16}c^4\delta + 1.55849\times 10^{18}c^2\delta^2 - 116415\delta^3,$

$\Psi_{14} = 436801c^6 - 2.66059\times 10^{10}c^4\delta + 4.55552\times 10^{12}c^2\delta^2 - 3.19183\times 10^{13}\delta^3,$

$\Psi_{15} = 71314c^{10} - 3.46416\times 10^9c^8\delta + 1.27178\times 10^{13}c^6\delta^2 - 9.89236\times 10^{15}c^4\delta^3 + 2.21466\times 10^{18}c^2\delta^4 - 7.27934\times 10^{19}\delta^5,$

$\Psi_{16} = 113105c^{10} - 3.7387\times 10^9c^8\delta + 1.2806\times 10^{13}c^6\delta^2 - 9.21033\times 10^{15}c^4\delta^3 + 1.70311\times 10^{18}c^2\delta^4 - 5.73055\times 10^{19}\delta^5$

5. Results and discussion

This section includes a numerical analysis for understanding the results. Sensitivity analysis has been conducted for the profit of supply chain members, greening level, total sales volume, retail price, and volume of strategic inventory. The following adjustments have been taken to the initial parameter values: $a = 1000, b = 8.5, h = 1, c = 10, \delta = 12$. For sensitivity analysis, the input parameters c and δ are adjusted in a certain way to ensure each of specified assumptions throughout the study are satisfied: $c \in [5, 15]$ and $\delta \in [5, 25]$.

Fig. 2 shows the implications of customer sensitivity on the product's greening level and the green investment parameter on the retailer's profit in different scenarios. It shows that the profit of the retailer increases as consumers are becoming more environmentally conscious and decreases while green investment expenditures increase. We investigate which scenario enables the retailer to make more profit than other scenarios. Proposition-1 explains that the retailer can gain higher profit in either the RS game or CS scenario. Fig. 3 shows the implications of customer sensitivity on the product's greening level and the green investment parameter on the wholesaler's profit in different scenarios. It shows that the profit of the wholesaler increases as consumers are becoming more environmentally conscious and decreases while green investment expenditures increase. We examine which scenario enables the wholesaler to make more profit than other scenarios. Proposition-2 indicates that the retailer can gain higher profit in either the WS game or CS scenario. In Fig. 4, we investigate the impact of consumer sensitivity on the product's greening level and the green investment parameter on the manufacturer's profit in different scenarios. The result indicates that the profit of the manufacturer increases as consumers are becoming more environmentally conscious and decrease while green investment expenditures increase. Proposition-3 clearly shows that the manufacturer must earn more money in the MS game. Also, it indicates that in the CS scenario, the manufacturer could really receive a higher financial gain than RS game and WS game scenarios except for some specific values of c and δ. In Fig. 5, the impact of the sensitivity of the customer to the greening level of the product and green investment parameter on the greening level of the manufacturer is investigated. It shows that the greening level of the manufacturer is proportional to the consumer sensitivity on the product's greening level and inversely related to the green investment parameter. Proposition-4 indicates that the manufacturer's greening level in the CS scenario is greater than any other scenario.

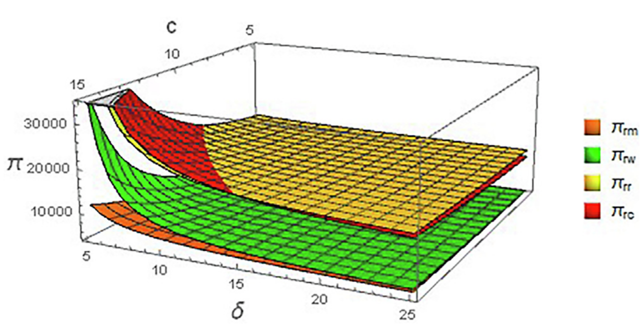

Fig. 2. Profit of the retailer in different game structures.

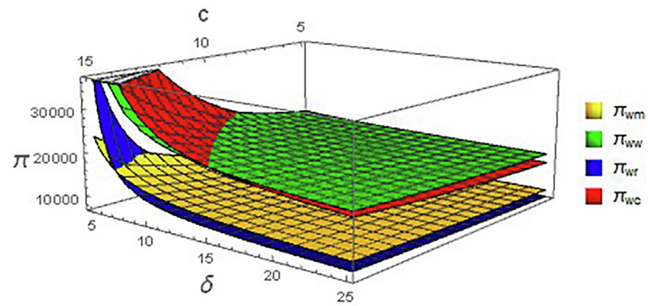

Fig. 3. Profit of the wholesaler in different game structures.

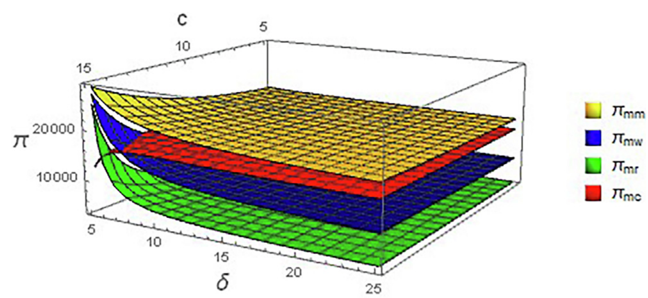

Fig. 4. Profit of the manufacturer in different game structures.

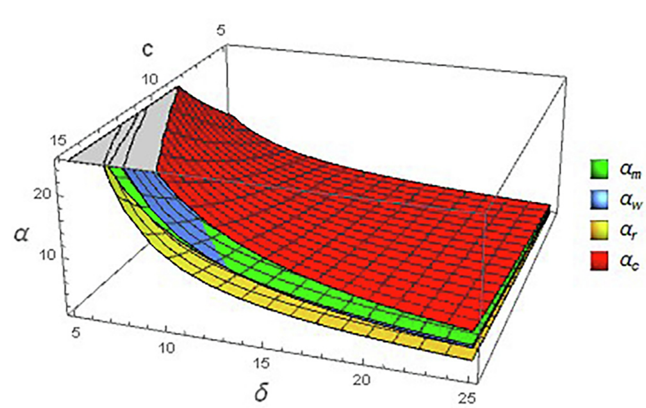

Fig. 5. Greening levels of the product in different game structures.

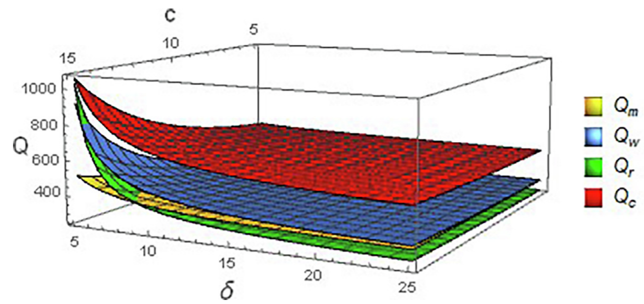

Fig. 6. Total sales volume of the product in different game structures.

Fig. 6 shows that the total sales volume of the product increases when the consumer sensitivity on the product's greening level increases and decreases when green investment expenditures increase. From proposition-5, we observe that the total sales volume of the product is maximum in the CS scenario. In Fig. 7–8, We examine how the consumer sensitivity on the product's greening level and the green investment parameter influence the retailer's unit selling price in both periods. Proposition-6 shows that the retailer's unit selling price of the product is maximum in the MS game scenario in the first period. And also, it reveals that in this period, the product's minimum unit selling price is determined by the retailer in the CS scenario except some specific values of c and δ. It seems from proposition-7 that in the CS scenario, the retailer sets the product's minimum unit selling price in the second period. In Fig. 9–12; we investigate the effect of the consumer sensitivity on the product's greening level and the green investment parameter on the retailer's unit selling price in MS game,

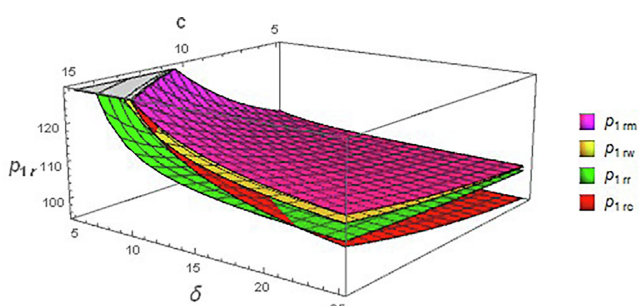

Fig. 7. The retailer's unit selling price of the product in the first period in different game structures.

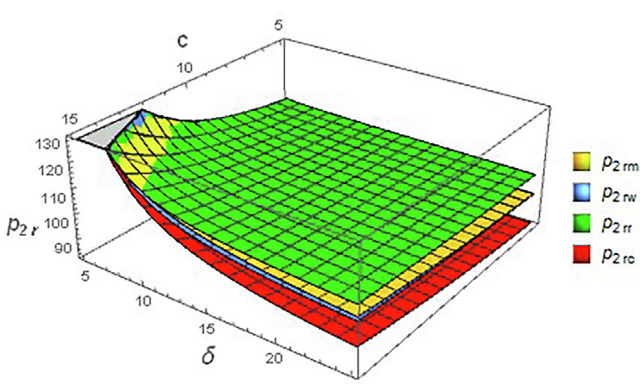

Fig. 8. The retailer's unit selling price of the product in the second period in different game structures.

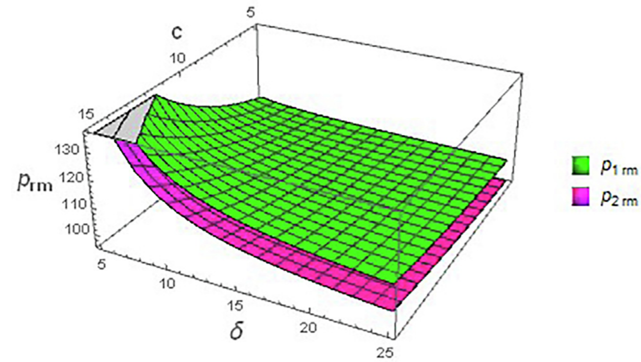

Fig. 9. The retailer's unit selling price of the product in the first and second period under MS game.

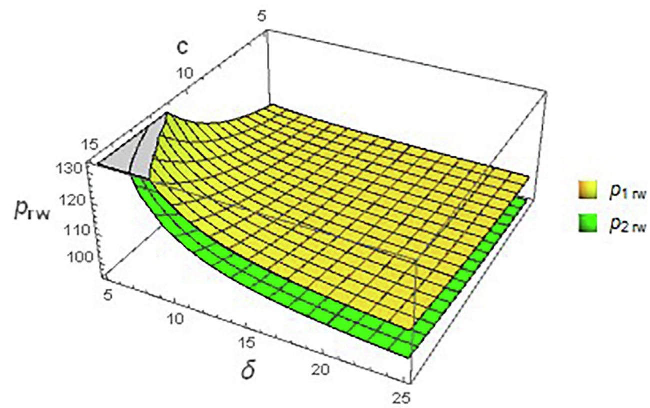

Fig. 10. The retailer's unit selling price of the product in the first and second period under WS game.

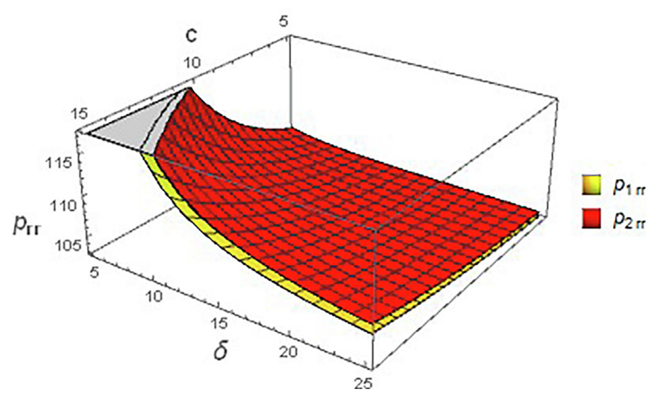

Fig. 11. The retailer's unit selling price of the product in the first and second period under RS game.

WS game, RS game, and CS scenarios. The result indicates that the green investment parameter is inversely proportional to the retailer's unit selling price, proportional to customer sensitivity on the product's greening level. Proposition-8 shows that the retailer's unit selling price in the second period is lower than the first period for MS game, WS game and, CS scenarios; in RS game, the retailer's unit selling price in the second period is greater than the first period. Fig. 13 shows that the volume of strategic inventory increases when the consumer sensitivity on the product's greening level increases and decreases when green investment expenditures increase. It seems from proposition-9

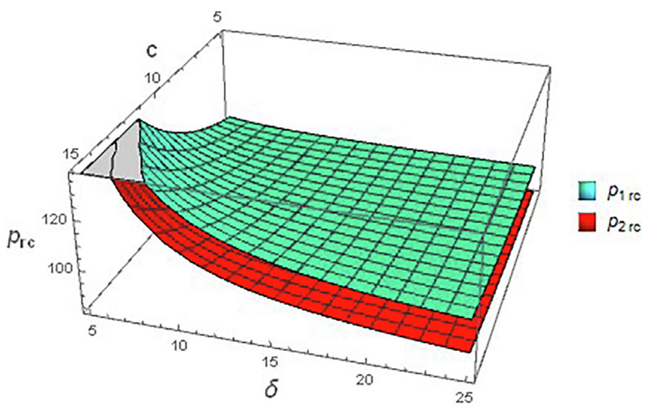

Fig. 12. The retailer's unit selling price of the product in the first and second period in centralised system.

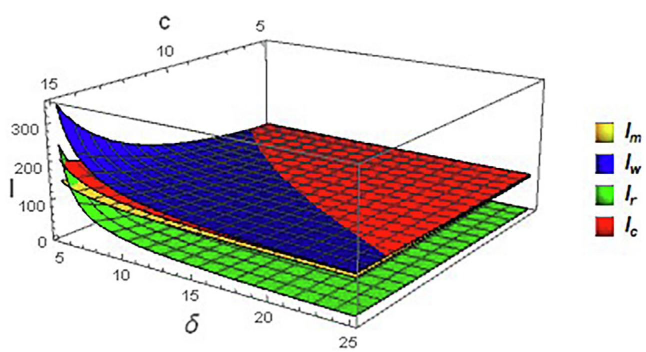

Fig. 13. volume of strategic inventory in different game structures.

that the volume of strategic inventory is higher in either WS game or CS scenarios than other scenarios except for some specific values c and δ.

After sensitivity tests, In order to demonstrate the findings of the CS scenario, we explore three cases using different parameters. In its second case, every parameter remains at its initial values. Take into consideration the article's assumptions; In the first case, the values of c and δ are reduced by 10%, while in the third case, the values of c and δ are increased by 10%. All other parameters remain the same. Table 2 presents the outcomes of the numerical investigation. Results indicate that in the centralized structure, supply chain stakeholders might compromise their marginal profit targets. The overall profit of the supply chain and the level of the greening of the products are significantly more significant in the centralized system than in any other game structure. Consumers will buy relatively less expensive products, and the retailer can sell a maximum number of products in the CS scenario. Results indicate that the retailer maintains a low level of strategic inventory in the RS game scenario. In this scenario, the product's retail price in the second period is higher than the retail price of the product in the first period. While in MS, WS, and CS scenarios, the retailer maintains a higher amount of strategic inventory. In these scenarios, the product's retail price in the second period is lower than the retailer price of the product in the first period. Therefore, a higher amount of strategic inventory leads the retailer to lower the retail price in the second period.

In this paper, a three-tier based green supply chain is considered in which the manufacturer invests and determines the level of greening in eco-friendly production processes. To achieve overall sustainability objectives, it is reasonable that the manufacturer becomes more effective in manufacturing green products. Due to the excessive deteriorating ecological situations, the manufacturing of eco-friendly and sustainable products or services has become extremely relevant. This kind of consciousness has an impact on the consumer. In contrast, Consumers have to pay more for green products. As a result, governments should provide green manufacturers with incentives to reduce selling prices in order to increase demand for eco-friendly products. When the outcomes of this paper are considered in this viewpoint, it's really apparent that as consumers become even more aware of a product's ecological impact, the manufacturer's green procurement level increases; the market for eco-friendly products increases; and hence overall supply chain gains even more. As a consequence, the supply chain's ecologically sustainable strategy inspires others as well as promotes a greener and more economically efficient one.

6. Conclusions

Investigating the relationships between ecological performance and eco-friendly manufacturing in order to maximize sales, environmental responsibility, and profitability is a recent research trend. The objective of this research is really to investigate in what way the supply chain leadership's decisions impact economic and environmental sustainability. According to this study, implementing one decision-maker in such a three-tiered green supply chain could significantly improve sustainability goals. Increasing the greening degree of the products, reducing the retail prices of the product, and enhancing overall supply chain financial gain are mostly common goals for a green supply chain. For ensuring successful implementation, stakeholders of the supply chain must also be needed to implement the centralized structure. In order to ensure sustainability, supply chain participants may even have to compromise on individual marginal profit targets. In this circumstance, the government has to provide

Table 2
Change of profits of the supply chain members, profit of the overall supply chain, greening level, total sales volume, retail price and volume of strategic inventory w.r.t change of c and δ.

	Case-1				Case-2				Case-3			
	$a = 1000$, $b = 8.5$, $h = 1$, $c = 9$, $\delta = 10.8$				$a = 1000$, $b = 8.5$, $h = 1$, $c = 10$, $\delta = 12$				$a = 1000$, $b = 8.5$, $h = 1$, $c = 11$, $\delta = 13.2$			
	MS	WS	RS	CS	MS	WS	RS	CS	MS	WS	RS	CS
π_r	5110.83	5547.82	16578.3	15584.6	5191.34	5695.32	16823.5	15924.3	5273.77	5849.42	17077.8	16275.2
π_w	10159.8	19630.3	8301.19	18347.4	10319.9	19914.7	8427.58	18748.1	10483.7	20207.4	8559.11	19162.1
π_m	18613.7	9903.59	4140.1	15860.6	18759.7	10035.3	4202.54	15924.6	18908.1	10171.1	4267.67	15987.6
π_{sc}	33884.33	35081.71	29019.59	49792.6	34270.94	35645.32	29453.62	50597	34665.57	36227.92	29904.58	51424.9
α	7.76988	7.12648	4.45002	10.7298	7.83083	7.23002	4.53283	10.8465	7.89276	7.33662	4.61862	10.9657
Q	335.873	350.111	277.867	548.284	338.509	354.722	281.516	554.232	341.187	359.469	285.297	560.311
p_1	110.692	109.043	105.527	103.006	111.561	109.755	105.902	104.126	112.443	110.488	106.292	105.27
p_2	101.541	100.153	106.5	90.5056	102.334	100.819	106.938	91.4853	103.14	101.505	107.392	92.4865
I	97.4497	106.423	6.39108	106.257	98.236	108.4	7.58985	107.446	99.0347	110.435	8.83034	108.662

incentives to the manufacturer to promote green manufacturing. Specific initiatives must therefore be incorporated by the government to guarantee that members of the supply chain conform to the centralized system. As a result, the supply chain is indeed capable of achieving success in both financial and environmental sense.

6.1. Practical implications, limitations and future research

For all strategic and operational decisions in a supply chain, this new research has significant practical implications. The result of this study may be used by the decision-makers of a supply chain to recognize the benefits of a centralized structure. The findings of the research suggest strategies to maximize the revenue of the overall supply chain. This analysis demonstrates how to improve product greening degrees and also how customers may purchase eco-friendly products at cheaper rates without compromising supply chain participants' total revenue. Participants of the supply chain could develop an ever more sustainable ecosystem by implementing the result of this research.

Even after recognizing its importance and utility, the present research has certain drawbacks. For instance, product shipping time wasn't considered. As a result, an effective approach for analyzing the impact of goods delivery time may really be useful. The concepts explored in this research can be expanded in numerous directions. The presented framework could be expanded by integrating supply channel coordination issues. The influence of the wholesaler's strategic inventory can even be examined across the same supply chain. Incorporating stochastic demand functions seems to be another prospective future research direction in this area.

Compliance with ethical standards

Ethical approval

None of the authors conducted any human or animal experiments for this paper.

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Informed consent

Every research participant was given the opportunity to give their informed consent.

Authorship contributions

The models were developed by Dr. Dipak Kumar Jana. Mr. Manojit has solved the issues in several scenarios, compared the optimal outcomes. The numerical section is performed by Dr. Shariful Alam. This article is written by Mr. Manojit Das.

Declaration of Competing Interest

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

Appendix A. Optimal decision in MS game scenario

The retailer's unit selling price in second-period is derived by solving $\frac{d\pi_{2rm}}{dp_{2rm}} = 0$, On simplification, $p_{2rm}(p_{2wm}, \alpha_m) = \frac{a+bp_{2w}+c\alpha_m}{2b}$. As $\frac{d^2\pi_{2rm}}{dp^2_{2rm}} = -2b < 0$, the profit function of the retailer is concave. Substituting p_{2rm} in Equation 3 and solving $\frac{d\pi_{2wm}}{dp_{2wm}} = 0$, the wholesaler's unit selling price in second-period is obtained as $p_{2wm}(p_{2mm}, \alpha_m) = \frac{a-2I_m+bp_{2mm}+c\alpha_m}{2b}$. As $\frac{d^2\pi_{2wm}}{dp^2_{2wm}} = -b < 0$, the profit function of the wholesaler is concave. Finally, the manufacturer's unit selling price in second-period is determined by solving $\frac{d\pi_{2mm}}{dp_{2mm}} = 0$. On simplification, $p_{2mm}(\alpha_m, I_m) = \frac{a-2I_m+c\alpha_m}{2b}$. As $\frac{d^2\pi_{2mm}}{dp^2_{2mm}} = -\frac{b}{2} < 0$, the profit function of the manufacturer is concave.

Substituting these equilibrium outcomes in Equation 5, the cumulative profit function for the retailer is obtained. The Hessian matrix of the objective function $\pi_{rm}(p_{1rm}, I_m)$ is calculated as

$$H(p_{1rm}, I_m) = \begin{bmatrix} \frac{\partial^2\pi_{rm}}{\partial p^2_{1rm}} & \frac{\partial^2\pi_{rm}}{\partial p_{1rm}\partial I_m} \\ \frac{\partial^2\pi_{rm}}{\partial I_m \partial p_{1rm}} & \frac{\partial^2\pi_{rm}}{\partial I^2_m} \end{bmatrix} = \begin{bmatrix} -2b & 0 \\ 0 & -\frac{15}{8b} \end{bmatrix}$$

The leading principal minors Δ_k of $H(p_{1rm}, I_m)$of order k are given by

$$H(p_{1rm}, I_m) = \begin{bmatrix} \frac{\partial^2\pi_{rm}}{\partial p^2_{1rm}} & \frac{\partial^2\pi_{rm}}{\partial p_{1rm}\partial I_m} \\ \frac{\partial^2\pi_{rm}}{\partial I_m \partial p_{1rm}} & \frac{\partial^2\pi_{rm}}{\partial I^2_m} \end{bmatrix} = \begin{bmatrix} -2b & 0 \\ 0 & -\frac{15}{8b} \end{bmatrix}$$

The leading principal minors Δ_k of $H(p_{1rm}, I_m)$of order k are given by

$$\Delta_1 = -2b < 0, \Delta_2 = \frac{15}{4} > 0$$

Therefore, $(-1)^k\Delta_k > 0$ for all leading principle minors of $H(p_{1rm}, I_m)$. Thus, $H(p_{1rm}, I_m)$ is negative definite and $\pi_{rm}(p_{1rm}, I_m)$ is concave. By solving $\frac{\partial\pi_{rm}}{\partial p_{1rm}} = 0$ and $\frac{\partial\pi_{rm}}{\partial I_m} = 0$ simultaneously, equilibrium outcomes are derived as follows:

$p_{1rm}(p_{1wm}, \alpha_m) = \frac{a+bp_{1wm}+c\alpha_m}{2b}$ and $I_m(p_{1wm}, \alpha_m) = \frac{(15a-16bh-16bp_{1wm}+15c\alpha_m)}{30}$.

By replacing these variables in Eq.(6), the cumulative profit function for the wholesaler is obtained. $p_{1wm}(p_{1mm}, \alpha_m) = \frac{450a-208bh+465bp_{1mm}+450c\alpha_m}{898b}$ is obtained by solving $\frac{d\pi_{wm}}{dp_{1wm}} = 0$. As $\frac{d^2\pi_{wm}}{dp^2_{1wm}} = -\frac{449b}{225} < 0$, the profit function of the wholesaler is concave.

Substituting these variables in Eq.(7), the cumulative profit function for the manufacturer is obtained. The Hessian matrix of the objective function $\pi_{mm}(p_{1mm}, \alpha_m)$ is calculated as

$$H(p_{1mm}, \alpha_m) = \begin{bmatrix} \frac{\partial^2\pi_{mm}}{\partial p^2_{1mm}} & \frac{\partial^2\pi_{mm}}{\partial p_{1mm}\partial \alpha_m} \\ \frac{\partial^2\pi_{mm}}{\partial \alpha_m \partial p_{1mm}} & \frac{\partial^2\pi_{mm}}{\partial \alpha^2_m} \end{bmatrix} = \begin{bmatrix} -\frac{416113b}{403202} & \frac{209297c}{403202} \\ \frac{209297c}{403202} & \frac{7200c^2}{201601b} - 4\delta \end{bmatrix}$$

The leading principal minors Δ_k of $H(p_{1mm}, \alpha_m)$of order k are given by

$$\Delta_1 = -\frac{416113b}{403202} < 0, \Delta_2 = \frac{3328904b\delta - 247009c^2}{806404} > 0$$

Therefore, $(-1)^k\Delta_k > 0$ for all leading principle minors of $H(p_{1mm}, \alpha_m)$. Thus, $H(p_{1mm}, \alpha_m)$ is negative definite and $\pi_{mm}(p_{1mm}, \alpha_m)$ is concave. By solving $\frac{\partial\pi_{mm}}{\partial p_{1mm}} = 0$ and $\frac{\partial\pi_{mm}}{\partial\alpha_m} = 0$ simultaneously, equilibrium outcomes are obtained as follows:

$p_{1mm} = \frac{1674376a\delta-765760bh\delta+29760hc^2}{3328904b\delta-247009c^2}$ and $\alpha_m = \frac{(247009a-53800bh\delta)c}{3328904b\delta-247009c^2}$.

Using the values of p_{1mm} and α_m the optimal solution is obtained which is shown in MS game scenario.

Appendix B. Optimal decision in WS game scenario

To obtain the optimal solution in WS game scenario, the transformation $m_{irw} = p_{irw} - p_{iww}$ and $m_{iww} = p_{iww} - p_{imw}$ $(i = 1, 2)$ is used. The retailer's unit profit margin in second-period is obtained by solving $\frac{d\pi_{2rw}}{dm_{2rw}} = 0$, On simplification, $m_{2rw}(p_{2mw}, \alpha_w) = \frac{a-b(p_{2mw}+m_{2ww})+c\alpha_w}{2b}$. As $\frac{d^2\pi_{2rw}}{dm^2_{2rw}} = -2b < 0$, the profit function of the retailer is concave. Substituting m_{2rw} in Eq.(4)solving $\frac{d\pi_{2mw}}{dp_{2mw}} = 0$, the manufacturer's unit selling price in second-period is obtained as $p_{2mw}(m_{2ww}, \alpha_w) = \frac{a-bm_{2ww}-2I_w+c\alpha_w}{2b}$.

As $\frac{d^2\pi_{2mw}}{dp_{2mw}^2} = -b < 0$, the profit function of the manufacturer is concave. Finally, the wholesaler's unit profit margin in second-period is derived by solving $\frac{d\pi_{2ww}}{dm_{2ww}} = 0$. On simplification, $m_{2ww}(\alpha_w, I_w) = \frac{a-2I_w+c\alpha_w}{2b}$. As $\frac{d^2\pi_{2ww}}{dm_{2ww}^2} = -\frac{b}{2} < 0$, the wholesaler's profit function is concave.

Substituting these equilibrium outcomes in Eq.(5), the cumulative profit function of the retailer is derived. The Hessian matrix of the objective function $\pi_{rw}(m_{1rw}, I_w)$ is calculated as

$$H(m_{1rw}, I_w) = \begin{bmatrix} \frac{\partial^2\pi_{rw}}{\partial m_{1rw}^2} & \frac{\partial^2\pi_{rw}}{\partial m_{1rw}\partial I_w} \\ \frac{\partial^2\pi_{rw}}{\partial I_w \partial m_{1rw}} & \frac{\partial^2\pi_{rw}}{\partial I_w^2} \end{bmatrix} = \begin{bmatrix} -2b & 0 \\ 0 & -\frac{15}{8b} \end{bmatrix}$$

The leading principal minors Δ_k of $H(m_{1rw}, I_w)$of order k are given by

$$\Delta_1 = -2b < 0, \Delta_2 = \frac{15}{4} > 0$$

Therefore, $(-1)^k\Delta_k > 0$ for all leading principle minors of $H(m_{1rw}, I_w)$. Thus, $H(m_{1rw}, I_w)$ is negative definite and $\pi_{rw}(m_{1rw}, I_w)$ is concave. By solving $\frac{\partial\pi_{rw}}{\partial m_{1rw}} = 0$ and $\frac{\partial\pi_{rw}}{\partial I_w} = 0$ simultaneously, equilibrium outcomes are derived as follows:

$m_{1rw}(p_{1mw}, \alpha_w) = \frac{a-b(p_{1mw}+m_{1ww})+c\alpha_w}{2b}$ and $I_w(p_{1mw}, \alpha_w) = \frac{15a-16bh-16b(p_{1mw}+m_{1ww})+15c\alpha_w}{30}$.

By replacing these variables in Eq.(7), the cumulative profit function of the manufacturer is derived. The Hessian matrix of the objective function $\pi_{mw}(p_{1mw}, \alpha_w)$ is calculated as

$$H(p_{1mw}, \alpha_w) = \begin{bmatrix} \frac{\partial^2\pi_{mw}}{\partial p_{1mw}^2} & \frac{\partial^2\pi_{mw}}{\partial p_{1mw}\partial \alpha_w} \\ \frac{\partial^2\pi_{mw}}{\partial \alpha_w \partial p_{1mw}} & \frac{\partial^2\pi_{mw}}{\partial \alpha_w^2} \end{bmatrix} = \begin{bmatrix} -\frac{449b}{225} & c \\ c & -4\delta \end{bmatrix}$$

The leading principal minors Δ_k of $H(p_{1mw}, \alpha_w)$of order k are given by

$$\Delta_1 = -\frac{449b}{225} < 0, \Delta_2 = \frac{1796b\delta - 225c^2}{225} > 0$$

Therefore, $(-1)^k\Delta_k > 0$ for all leading principle minors of $H(p_{1mw}, \alpha_w)$. Thus, $H(p_{1mw}, \alpha_w)$ is negative definite and $\pi_{mw}(p_{1mw}, \alpha_w)$ is concave. By solving $\frac{\partial\pi_{mw}}{\partial p_{1mw}} = 0$ and $\frac{\partial\pi_{mw}}{\partial \alpha_w} = 0$ simultaneously, optimal response is obtained as follows:

$p_{1mw}(m_{1ww}) = \frac{2(450a-208bh-433bm_{1ww})\delta}{1796b\delta-225c^2}$ and $\alpha_w(m_{1ww}) = \frac{(450a-208bh-433bm_{1ww})c}{2(1796b\delta-225c^2)}$.

Substituting these variables in Eq.(6), the cumulative profit function for the wholesaler is obtained. $m_{1ww} = \frac{a\delta(837188b\delta-111825c^2)+8h(225c^4+4601bc^2\delta-47860b^2\delta^2)}{433b\delta(3844b\delta-497c^2)}$ is obtained by solving $\frac{d\pi_{ww}}{dm_{1ww}} = 0$. As $\frac{d^2\pi_{ww}}{dm_{1ww}^2} = -\frac{866b^2\delta(3844b\delta-497c^2)}{(1796b\delta-225c^2)^2} < 0$, the wholesaler's profit function is concave.

Using the value of m_{1ww} the optimal solution is obtained which is shown in WS game scenario.

Appendix C. Optimal decision in RS game scenario

To obtain the optimal solution in RS game scenario, the transformation $m_{irw} = p_{irw} - p_{iww}$ and $m_{iww} = p_{iww} - p_{imw}$ $(i = 1, 2)$ is used. The manufacturer's unit selling price in second-period is obtained by solving $\frac{d\pi_{2mr}}{dp_{2mr}} = 0$, On simplification, $p_{2mr}(m_{2wr}, m_{2rr}, I_r, \alpha_r) = \frac{a-I_r-bm_{2rr}-bm_{2wr}+c\alpha_r}{2b}$. As $\frac{d^2\pi_{2mr}}{dp_{2mr}^2} = -2b < 0$, the profit function of the manufacturer is concave. Substituting p_{2mr} in Eq. (3) the wholesaler's unit profit margin in second-period is derived by solving $\frac{d\pi_{2wr}}{dm_{2wr}} = 0$, On simplification, $m_{2wr}(m_{2rr}, I_r, \alpha_r) = \frac{a-I_r-bm_{2rr}+c\alpha_r}{2b}$. As $\frac{d^2\pi_{2wr}}{dm_{2wr}^2} = -b < 0$, the wholesaler's profit function is concave. Substituting m_{2wr} in Eq.(2)solving $\frac{d\pi_{2rr}}{dm_{2rr}} = 0$, the retailer's unit profit margin in second-period is obtained as $m_{2rr}(\alpha_r) = \frac{a+c\alpha_r}{2b}$. As $\frac{d^2\pi_{2rr}}{dm_{2rr}^2} = -\frac{b}{2} < 0$, the retailer's profit function is concave.

Substituting these equilibrium outcomes in Eq.(7), the cumulative profit function of the manufacturer is derived. The Hessian matrix of the objective function $\pi_{mr}(p_{1mr}, \alpha_r)$ is calculated as

$$H(p_{1mr}, \alpha_r) = \begin{bmatrix} \frac{\partial^2\pi_{mr}}{\partial p_{1mr}^2} & \frac{\partial^2\pi_{mr}}{\partial p_{1mr}\partial \alpha_r} \\ \frac{\partial^2\pi_{mr}}{\partial \alpha_r \partial p_{1mr}} & \frac{\partial^2\pi_{mr}}{\partial \alpha_r^2} \end{bmatrix} = \begin{bmatrix} -2b & c \\ c & \frac{c^2}{32b} - 4\delta \end{bmatrix}$$

The leading principal minors Δ_k of $H(p_{1mr}, \alpha_r)$of order k are given by

$$\Delta_1 = -2b < 0, \Delta_2 = \frac{128b\delta - 17c^2}{16} > 0$$

Therefore, $(-1)^k\Delta_k > 0$ for all leading principle minors of $H(p_{1mr}, \alpha_r)$. Thus, $H(p_{1mr}, \alpha_r)$ is negative definite and $\pi_{mr}(p_{1mr}, \alpha_r)$ is concave. By solving $\frac{\partial\pi_{mr}}{\partial p_{1mr}} = 0$ and $\frac{\partial\pi_{mr}}{\partial \alpha_r} = 0$ simultaneously, equilibrium outcomes are derived as follows:

$p_{1mr}(m_{1wr}, m_{1rr}, I_r) = 128ab\delta - 128b^2\delta m_{1rr} - 128b^2\delta m_{1wr} + 128b\delta I_r \frac{+c^2bm_{1rr}+c^2bm_{1wr}-3c^2I_r}{2b(128b\delta-17c^2)}$and $\alpha_r(m_{1wr}, m_{1rr}, I_r) = \frac{c(17a-16bm_{1rr}-16bm_{1wr}+14I_r)}{128b\delta-17c^2}$

By replacing these variables in Eq.(6), the cumulative profit function for the wholesaler is obtained. $m_{1wr}(m_{1rr}, I_r) = \frac{128ab\delta(128b\delta-19c^2)+I_r(16384b^2\delta^2-2048c^2b\delta-45c^4)+bm_{1rr}(15c^4-16384b^2\delta^2+2304c^2b\delta)}{2b(c^4+16384b^2\delta^2-2304c^2b\delta)}$ is obtained by solving $\frac{d\pi_{wr}}{dm_{1wr}} = 0$. As $\frac{d^2\pi_{wr}}{dm_{1wr}^2} = -\frac{b(16384b^2\delta^2-2304c^2b\delta+c^4)}{(128b\delta-17c^2)^2} < 0$, the wholesaler's profit function is concave.

Substituting the optimal response in Eq.(5), the cumulative profit function for the retailer is obtained. The Hessian matrix of the objective function $\pi_{rr}(m_{1rr}, I_r)$ is calculated as

$$H(m_{1rr}, I_r) = \begin{bmatrix} \frac{\partial^2\pi_{rr}}{\partial m_{1rr}^2} & \frac{\partial^2\pi_{rr}}{\partial m_{1rr}\partial I_r} \\ \frac{\partial^2\pi_{rr}}{\partial I_r \partial m_{1rr}} & \frac{\partial^2\pi_{rr}}{\partial I_r^2} \end{bmatrix}$$

$$= \begin{bmatrix} -\frac{b(128b\delta-c^2)^2(16384b^2\delta^2-2304c^2b\delta-15c^4)}{2(16384b^2\delta^2-2304c^2b\delta+c^4)^2} \\ \frac{2097152c^2b^3\delta^3-540672c^4b^2\delta^2+14208c^6b\delta-47c^8}{2(16384b^2\delta^2-2304c^2b\delta+c^4)^2} \\ \frac{2097152c^2b^3\delta^3-540672c^4b^2\delta^2+14208c^6b\delta-47c^8}{2(16384b^2\delta^2-2304c^2b\delta+c^4)^2} \\ \frac{139c^8-8388608b^3\delta^3(192b\delta-55c^2)-256b\delta c^4(127680b\delta+139c^2)}{2b(16384b^2\delta^2-2304c^2b\delta+c^4)^2} \end{bmatrix}$$

The leading principal minors Δ_k of $H(m_{1rr}, I_r)$of order k are given by

$$\Delta_1 = -\frac{b(128b\delta-c^2)^2(16384b^2\delta^2-2304c^2b\delta-15c^4)}{2(16384b^2\delta^2-2304c^2b\delta+c^4)^2} < 0,$$
$$\Delta_2 = \frac{402653184b^4\delta^4-65011712c^2b^3\delta^3+434176c^4b^2\delta^2+4224c^6b\delta-31c^8}{(16384b^2\delta^2-2304c^2b\delta+c^4)^2} > 0$$

Therefore, $(-1)^k\Delta_k > 0$ for all leading principle minors of $H(m_{1rr}, I_r)$. Thus, $H(m_{1rr}, I_r)$ is negative definite and $\pi_{rr}(m_{1rr}, I_r)$ is concave. By solving $\frac{\partial\pi_{rr}}{\partial m_{1rr}} = 0$ and $\frac{\partial\pi_{rr}}{\partial I_r} = 0$ simultaneously, optimal response is obtained as follows:

$m_{1rr} = 402653184ab^3\delta^4 - 68157440ac^2b^2\delta^3 + 532480ac^4b\delta^2 - 8256ac^6 \frac{\delta-2097152c^2b^3h\delta^3+540672c^4b^2h\delta^2-14208c^6bh\delta+47c^8h}{2(402653184b^4\delta^4-65011712c^2b^3\delta^3+434176c^4b^2\delta^2+4224c^6b\delta-31c^8)}$ and $I_r = 7340032ac^2b^3\delta^3 - 114688ac^4b^2\delta^2 + \frac{320ac^6b\delta-268435456b^5h\delta^4+41943040c^2b^4h\delta^3-360448c^4b^3h\delta^2-1536c^6b^2h\delta+15c^8bh}{2(402653184b^4\delta^4-65011712c^2b^3\delta^3+434176c^4b^2\delta^2+4224c^6b\delta-31c^8)}$.

Using the values of m_{1rr} and I_r the optimal solution is obtained which is shown in RS game scenario.

Appendix D. Optimal decision in CS game scenario

To obtain the optimal solution in CS game scenario, the transformation $m_{irw} = p_{irw} - p_{iww}$ and $m_{iww} = p_{iww} - p_{imw}$ $(i = 1, 2)$ is used. The reatailer's and wholesaler's unit profit margin and the manufacturer's unit selling price in second-period is obtained by solving $\frac{d\pi_{2rc}}{dm_{2rc}} = 0, \frac{d\pi_{2wc}}{dm_{2wc}} = 0, \frac{d\pi_{2mc}}{dp_{2mc}} = 0$ simultaneously; On simplification, $m_{2rc}(I_c, \alpha_c) = \frac{a+2I_c+c\alpha_c}{4b}, m_{2wc}(I_c, \alpha_c) = \frac{a-2I_c+c\alpha_c}{4b}$ and $p_{2mc}(I_c, \alpha_c) = \frac{a-2I_c+c\alpha_c}{4b}$. As $\frac{d^2\pi_{2rc}}{dm_{2rc}^2} = -2b < 0, \frac{d^2\pi_{2wc}}{dm_{2wc}^2} = -2b < 0$ and $\frac{d^2\pi_{2mc}}{dp_{2mc}^2} = -2b < 0$; the retailer's, wholesaler's and manufacturer's profit function is concave.

Substituting these equilibrium outcomes in Eq.(5)–(7), the cumulative profit function for the retailer, wholesaler and manufacturer is obtained.

The Hessian matrix of the objective function $\pi_{rc}(m_{1rc}, I_c)$ is calculated as

$$H(m_{1rc}, I_c) = \begin{bmatrix} \frac{\partial^2 \pi_{rc}}{\partial m_{1rc}^2} & \frac{\partial^2 \pi_{rc}}{\partial m_{1rc} \partial I_c} \\ \frac{\partial^2 \pi_{rc}}{\partial I_c \partial m_{1rc}} & \frac{\partial^2 \pi_{rc}}{\partial I_c^2} \end{bmatrix} = \begin{bmatrix} -2b & 0 \\ 0 & -\frac{3}{2b} \end{bmatrix}$$

The leading principal minors Δ_k of $H(m_{1rc}, I_c)$of order k are given by

$$\Delta_1 = -2b < 0, \Delta_2 = 3 > 0$$

Therefore, $(-1)^k \Delta_k > 0$ for all leading principle minors of $H(m_{1rc}, I_c)$. Thus, $H(m_{1rc}, I_c)$ is negative definite and $\pi_{rc}(m_{1rc}, I_c)$ is concave.

As $\frac{d^2\pi_{wc}}{dm_{1wc}^2} = -2b < 0$, the wholesaler's profit function is concave.

The Hessian matrix of the objective function $\pi_{mc}(p_{1mc}, \alpha_c)$ is calculated as

$$H(p_{1mc}, \alpha_c) = \begin{bmatrix} \frac{\partial^2 \pi_{mc}}{\partial p_{1mc}^2} & \frac{\partial^2 \pi_{mc}}{\partial p_{1mc} \partial \alpha_c} \\ \frac{\partial^2 \pi_{mc}}{\partial \alpha_c \partial p_{1mc}} & \frac{\partial^2 \pi_{mc}}{\partial \alpha_c^2} \end{bmatrix} = \begin{bmatrix} -2b & c \\ c & \frac{c^2}{8b} - 4\delta \end{bmatrix}$$

The leading principal minors Δ_k of $H(p_{1mc}, \alpha_c)$of order k are given by

$$\Delta_1 = -2b < 0, \Delta_2 = \frac{32b\delta - 5c^2}{4} > 0$$

Therefore, $(-1)^k \Delta_k > 0$ for all leading principle minors of $H(p_{1mc}, \alpha_c)$. Thus, $H(p_{1mc}, \alpha_c)$ is negative definite and $\pi_{mc}(p_{1mc}, \alpha_c)$ is concave.

By solving $\frac{\partial \pi_{rc}}{\partial m_{1rc}} = 0, \frac{\partial \pi_{rc}}{\partial I_c} = 0, \frac{d\pi_{wc}}{dm_{1wc}} = 0, \frac{\partial \pi_{mc}}{\partial p_{1mc}} = 0$ and $\frac{\partial \pi_{mc}}{\partial \alpha_c} = 0$ simultaneously, optimal response is obtained as follows:

$m_{1rc} = \frac{8a\delta+8bh\delta-hc^2}{4(10b\delta-c^2)}, I_c = \frac{b\left(8a\delta-32bh\delta+3c^2h\right)}{8(10b\delta-c^2)}, m_{1wc} = \frac{24a\delta-16bh\delta+c^2h}{8(10b\delta-c^2)}, \quad p_{1mc} = \frac{24a\delta-16bh\delta+c^2h}{8(10b\delta-c^2)}$ and.

$\alpha_c = \frac{c(4a-bh)}{4(10b\delta-c^2)}$

Using these values the optimal solution is obtained which is shown in CS game scenario.

Appendix E. Proof of Proposition-1

$$\begin{aligned}
&\pi_{rw} - \pi_{rm} \\
&= \frac{c^2}{1499912b\delta^2(247009c^2 - 3328904b\delta)^2(497c^2 - 3844b\delta)^2} \\
&\times \left[497a^2\delta^2(213448402541187023c^6 + 153029943943939741568b^3\delta^3\right. \\
&- 91565899432464856728c^2b^2\delta^2 - 874708112504776368 0c^4b\delta) \\
&- 2ah\delta(1707587220329496184c^8 + 5877548358030846090291 20b^4\delta^4 \\
&- 110745298304106359173536c^2b^3\delta^3 + 7285647893217815851828c^4b^2\delta^2 \\
&- 2280440367810372003 11c^6b\delta) + 16h^2(1717894587856636c^{10} \\
&+ 143680439114966810895 36b^5\delta^5 - 2389060409577101724608c^2b^4\delta^4 \\
&+ 575189788673593180 52c^4b^3\delta^3 + 74753045331966004 37c^6b^2\delta^2 \\
&\left.-388442077023835303c^8b\delta)\right] \geqslant 0
\end{aligned}$$

$$\begin{aligned}
\pi_{rr} - \pi_{rw} = {} & \frac{1}{1499912b\delta^2(497c^2 - 3844b\delta)^2(402653184b^4\delta^4 - 65011712c^2b^3\delta^3 + 434176c^4b^2\delta^2 + 4224c^6b\delta - 31c^8)} \\
& \left[a^2\delta^2(53899586881c^{12} + 7755763699180445368 32b^6\delta^6 - 2644189543639422074 88c^2b^5\delta^5 + 26943132292447010816c^4b^4\delta^4\right. \\
& -671301098206602240c^6b^3\delta^3 + 6582570297247160c^8b^2\delta^2 - 8100256141712c^{10}b\delta) + 2ah\delta(852543821616072622 08b^7\delta^7 \\
& - 867598984c^{14} - 4330410981789270016 0c^2b^6\delta^6 + 8245608703161794560c^4b^5\delta^5 - 627838130456885248c^6b^4\delta^4 \\
& + 8076684405009248c^8b^3\delta^3 - 30946204204748c^{10}b^2\delta^2 + 210698042089c^{12}b\delta) + 2h^2(6982688c^{16} + 1048667682648233082 88b^8\delta^8 \\
& - 45729638730392666112c^2b^7\delta^7 + 6620561586423070720c^4b^6\delta^6 - 334666121699368960c^6b^5\delta^5 + 3059491199857936c^8b^4\delta^4 \\
& \left.-5329372674088c^{10}b^3\delta^3 + 197274745577c^{12}b^2\delta^2 - 2342130120c^{14}b\delta)\right]
\end{aligned}$$

$$\begin{aligned}
\pi_{rc} - \pi_{rw} = {} & \frac{1}{11999296b\delta^2(3844b\delta - 497c^2)^2(10b\delta - c^2)^2} \\
& \left[8a^2\delta^2(159371669581152b^4\delta^4 - 1738696351c^8\right. \\
& - 43718312584032c^2b^3\delta^3 + 2569560337972c^4b^2\delta^2 \\
& + 59161112668c^6b\delta) + 16ah\delta(27987064c^{10} \\
& + 43336358533632b^5\delta^5 - 15512591482784c^2b^4\delta^4 \\
& + 1880187209332c^4b^3\delta^3 - 48827661283c^6b^2\delta^2 \\
& - 3542989143c^8b\delta) + h^2(298499345104896b^6\delta^6 \\
& - 3603968c^{12} - 167823639893248c^2b^5\delta^5 \\
& + 33354220749616c^4b^4\delta^4 - 2837375464616c^6b^3\delta^3 \\
& \left.+81676867403c^8b^2\delta^2 + 789851008c^{10}b\delta)\right]
\end{aligned}$$

$$\begin{aligned}
\pi_{rc} - \pi_{rr} = {} & \frac{b}{64(10b\delta - c^2)^2(31c^8 - 402653184b^4\delta^4 + 65011712c^2b^3\delta^3 - 434176c^4b^2\delta^2 - 4224c^6b\delta)} \\
& \left[64a^2\delta^2(19797c^8 + 603979776b^4\delta^4 - 475004928c^2b^3\delta^3 + 84201472c^4b^2\delta^2 - 2270592^6b\delta)\right. \\
& - 16ah\delta(733c^{10} + 3221225472b^5\delta^5 - 260046848c^2b^4\delta^4 - 118030336c^4b^3\delta^3 + 18062848c^6b^2\delta^2 \\
& - 255096c^8b\delta) + h^2(101c^{12} + 17179869184b^6\delta^6 - 2684354560c^2b^5\delta^5 - 102760448c^4b^4\delta^4 + 17137664c^6b^3\delta^3 \\
& \left.+1386048c^8b^2\delta^2 - 23536c^{10}b\delta)\right]
\end{aligned}$$

$\pi_{rc} - \pi_{rr} > 0$ in the region bounded by $8.79 < c \leq 15, 5 \leqslant \delta \leq 14.56$ and the curve $\Psi_1 = 0$; $\pi_{rc} - \pi_{rr} \leqslant 0$ for all other values of c and δ.

Appendix F. Proof of Proposition-2

$$\pi_{ww} - \pi_{wr} = \frac{1}{3464\delta(3844b\delta - 497c^2)(402653184b^4\delta^4 - 65011712c^2b^3\delta^3 + 434176c^4b^2\delta^2 + 4224c^6b\delta - 31c^8)^2}$$
$$\big[8a^2\delta^2(237375649c^{16} + 2318140988716154565427 2b^8\delta^8 - 741326768243598163968 0c^2b^7\delta^7 + 5441248190179731046 40c^4b^6\delta^6$$
$$+840004699685283430 4c^6b^5\delta^5 - 30666707955194265 6c^8b^4\delta^4 + 4200900074405888c^{10}b^3\delta^3 - 30492736366592c^{12}b^2\delta^2$$
$$+ 52215376640c^{14}b\delta) - 128ah\delta(477617c^{18} + 1090321469786397081600b^9\delta^9 - 373989292446612193280c^2b^8\delta^8$$
$$+ 349333920671177113 60c^4b^7\delta^7 - 640168820396261376c^6b^6\delta^6 + 23209811101351936c^8b^5\delta^5 - 748447375163392c^{10}b^4\delta^4$$
$$+ 8090569357312c^{12}b^3\delta^3 - 19400745640c^{14}b^2\delta^2 - 121543601c^{16}b\delta) + h^2(492032c^{20} + 8961644443790213958860 8b^{10}\delta^{10}$$
$$- 378755183123655630520 32c^2b^9\delta^9 + 533300877349253178982 4c^4b^8\delta^8 - 265552708173224214528c^6b^7\delta^7$$
$$+ 18524089810797199 36c^8b^6\delta^6 + 72827842206892032c^{10}b^5\delta^5 - 1279330970730496c^{12}b^4\delta^4 + 5595118533120c^{14}b^3\delta^3$$
$$+19876155324c^{16}b^2\delta^2 - 223544287c^{18}b\delta)\big]$$

$$\pi_{wc} - \pi_{wr} = \frac{b}{64(10b\delta - c^2)^2(402653184b^4\delta^4 - 65011712c^2b^3\delta^3 + 434176c^4b^2\delta^2 + 4224c^6b\delta - 31c^8)^2}$$
$$\big[64a^2\delta^2(1094374709451030528b^8\delta^8 - 530739c^{16} - 277393589548351488c^2b^7\delta^7 - 43980465111040c^4b^6\delta^6$$
$$+ 3264746375610368c^6b^5\delta^5 - 117038882226176c^8b^4\delta^4 + 1214130159616c^{10}b^3\delta^3 - 12415232000c^{12}b^2\delta^2$$
$$+ 134534400c^{14}b\delta) - 16ah\delta(321c^{18} + 2594073385365405696b^9\delta^9 - 1069604911500492800c^2b^8\delta^8$$
$$+ 164768414492000256c^4b^7\delta^7 - 14650580123254784c^6b^6\delta^6 + 892626274353152c^8b^5\delta^5 - 18003924090880c^{10}b^4\delta^4$$
$$+ 204329058304c^{12}b^3\delta^3 - 1347512832c^{14}b^2\delta^2 + 3665680c^{16}b\delta) + h^2(4797c^{20} + 5418731071652180787 2b^{10}\delta^{10}$$
$$- 2804841847926344908 8c^2b^9\delta^9 + 5432396681771483136c^4b^8\delta^8 - 475799363268902912c^6b^7\delta^7 + 16629129822601216c^8b^6\delta^6$$
$$-9244313124864c^{10}b^5\delta^5 - 4949410578432c^{12}b^4\delta^4 + 52909789184c^{14}b^3\delta^3 - 59076896c^{16}b^2\delta^2 - 1371840c^{18}b\delta)\big] \geqslant 0$$

$$\pi_{ww} - \pi_{wm} = \frac{1}{433\delta(3328904b\delta - 247009c^2)^2(3844b\delta - 497c^2)}$$
$$\big[a^2\delta^2(15070870303021729c^4 + 134074996733191529 6b^2\delta^2 - 225658266588265224c^2b\delta) - 16ah\delta(30323682702257c^6$$
$$+ 34466558524795552b^3\delta^3 - 221773012579816c^2b^2\delta^2 - 426556133873163c^4b\delta) + 8h^2(488107568648c^8$$
$$+7763386360746649 6b^4\delta^4 - 18355510477388480c^2b^3\delta^3 + 1556076478909980c^4b^2\delta^2 - 50183349088369c^6b\delta)\big] \geqslant 0$$

$$\pi_{wc} - \pi_{wm} = \frac{b}{64(3328904b\delta - 247009c^2)^2(10b\delta - c^2)^2}$$
$$\big[64a^2\delta^2(60159009893408b^2\delta^2 - 45843341371c^4 - 4598637643056c^2b\delta) - 16ah\delta(66823359937c^6$$
$$+ 23281260665856b^3\delta^3 + 16154851045184c^2b^2\delta^2 - 2324765324032c^4b\delta) + h^2(181515535045c^8$$
$$+3147742962286592b^4\delta^4 - 1065587748812800c^2b^3\delta^3 + 139898587511104c^4b^2\delta^2 - 8258526378416c^6b\delta)\big] \geqslant 0$$

$$\pi_{wr} - \pi_{wm} = -\frac{b}{8(3328904b\delta - 247009c^2)^2(402653184b^4\delta^4 - 65011712c^2b^3\delta^3 + 434176c^4b^2\delta^2 + 4224c^6b\delta - 31c^8)^2}$$
$$\big[64a^2\delta^2(2967336739789094870618996736b^8\delta^8 - 4042269988565791c^{16}$$
$$- 629714943016838466115731456c^2b^7\delta^7 138310315257880817210228736c^4b^6\delta^6$$
$$+ 3008729583290753115750400 0c^6b^5\delta^5 - 948985818261609200484352c^8b^4\delta^4$$
$$+ 9897509860488196390912c^{10}b^3\delta^3 - 101816424015828406272c^{12}b^2\delta^2 + 1053359793629009152c^{14}b\delta)$$
$$+ 256ah\delta(348686974277c^{18} - 1950930252857342285234307072b^9\delta^9 + 978508750511164281849905152C^2b^8\delta^8$$
$$- 164424004053793870620655616c^4b^7\delta^7 + 12315891939495370924490752c^6b^6\delta^6 - 505182067214304730415104c^8b^5\delta^5$$
$$+ 8963159923595412504576c^{10}b^4\delta^4 - 97653406309941231616c^{12}b^3\delta^3 + 651680910787867968c^{14}b^2\delta^2 - 1890387258455652c^{16}b\delta)$$
$$+ h^2(14780633959039c^{20} + 11267492131789957906367198003 2b^{10}\delta^{10} - 55431515784189524574224777216c^2b^9\delta^9$$
$$+ 8734531843602032919498981376c^4b^8\delta^8 - 462759180122495691515756544c^6b^7\delta^7 - 37947628359555826707333 12c^8b^6\delta^6$$
$$+ 1121512859757872737681408c^{10}b^5\delta^5 - 27285948754683621801984c^{12}b^4\delta^4 + 228272129499670093824c^{14}b^3\delta^3$$
$$- 328977414336585792c^{16}b^2\delta^2 - 4218931414175856c^{18}b\delta)$$

$\pi_{wr} - \pi_{wm} > 0$ in the region bounded by $12.82 \leqslant c \leq 15, 5 \leqslant \delta < 6.84$ and the curve $\Psi_2 = 0$; $\pi_{wr} - \pi_{wm} \leqslant 0$ for all other values of c and δ.

$$
\begin{aligned}
\pi_{wc} - \pi_{wm} = {} & \frac{b}{64(3328904b\delta - 247009c^2)^2(10b\delta - c^2)^2} \\
& \big[64a^2\delta^2(60159009893408b^2\delta^2 - 45843341371c^4 \\
& - 4598637643056c^2b\delta) - 16ah\delta(66823359937c^6 \\
& + 23281260665856b^3\delta^3 + 16154851045184c^2b^2\delta^2 \\
& - 2324765324032c^4b\delta) + h^2(181515535045c^8 \\
& + 3147742962286592b^4\delta^4 - 1065587748812800c^2b^3\delta^3 \\
& + 139898587511104c^4b^2\delta^2 - 8258526378416c^6b\delta)\big] \geqslant 0
\end{aligned}
$$

$$
\begin{aligned}
\pi_{wc} - \pi_{ww} = {} & \frac{1}{27712\delta(10b\delta - c^2)^2(3844b\delta - 497c^2)} \\
& \big[64a^2\delta^2(2142567c^2b\delta - 247009c^4 - 3063024b^2\delta^2) \\
& + 16ah\delta(31808c^6 + 16408768b^3\delta^3 - 3648436c^2b^2\delta^2 \\
& + 9441c^4b\delta) + h^2(114100224b^4\delta^4 - 4096c^8 - 47700864c^2b^3\delta^3 \\
& + 6261044c^4b^2\delta^2 - 247589c^6b\delta)\big]
\end{aligned}
$$

$\pi_{wc} - \pi_{ww} > 0$ in the region bounded by $8.72 \leqslant c \leq 15, 5 \leqslant \delta \leq 14.82$ and the curve $\Psi_3 = 0$; $\pi_{wc} - \pi_{ww} \leqslant 0$ for all other values of c and δ.

Appendix G. Proof of Proposition-3

$$
\begin{aligned}
\pi_{mw} - \pi_{mr} = {} & \frac{1}{2999824b\delta^2(3844b\delta - 497c^2)^2(402653184b^4\delta^4 - 65011712c^2b^3\delta^3 + 434176c^4b^2\delta^2 + 4224c^6b\delta - 31c^8)^2}[8a^2\delta^2(854552336400c^{20} \\
& + 399420895407137057224607662 08b^{10}\delta^{10} - 187053716469087443901543874 56c^2b^9\delta^9 + 294245481759053325445942476 8c^4b^8\delta^8 \\
& - 16256450079779100292231987 2c^6b^7\delta^7 + 6925557664880551820001 28c^8b^6\delta^6 + 66134430318431984418816c^{10}b^5\delta^5 \\
& - 1620818489158916161536c^{12}b^4\delta^4 + 16183926181031545920c^{14}b^3\delta^3 - 57167768897334940c^{16}b^2\delta^2 - 112158692676989c^{18}b\delta) \\
& - 64ah\delta(3438842400c^{22} + 39018605057146845704686141 44b^{11}\delta^{11} - 18933009391723308580801085 44c^2b^{10}\delta^{10} \\
& + 31981479744506269767879884 8c^4b^9\delta^9 - 21339070441526212377444352c^6b^8\delta^8 + 443670700877597791748096c^8b^7\delta^7 \\
& - 5541614551949600227328c^{10}b^6\delta^6 + 29956840944594410 5984c^{12}b^5\delta^5 - 6448853145585733200c^{14}b^4\delta^4 \\
& + 47454675252856720c^{16}b^3\delta^3 - 202975355275 91c^{18}b^2\delta^2 - 1124603475074c^{20}b\delta) + h^2(1771315200c^{24} \\
& + 15615165650448694949622631 6288b^{12}\delta^{12} - 89290908981100993857693155 328c^2b^{11}\delta^{11} \\
& + 19598868606303315914538352 640c^4b^{10}\delta^{10} - 20482597068788384936063139 84c^6b^9\delta^9 + 10126068485027996110526873 6c^8b^8\delta^8 \\
& - 19180647274928466087116 80c^{10}b^7\delta^7 - 83551963754727709081 6c^{12}b^6\delta^6 + 450518435086678682112c^{14}b^5\delta^5 \\
& - 5125607113976247312c^{16}b^4\delta^4 + 12480739074534824c^{18}b^3\delta^3 + 129310203722543c^{20}b^2\delta^2 - 926062807552c^{22}b\delta)] \\
& \geqslant 0
\end{aligned}
$$

$$
\begin{aligned}
\pi_{mm} - \pi_{mw} = {} & \frac{1}{374978b\delta^2(3844b\delta - 497c^2)^2(3328904b\delta - 247009c^2)}[a^2\delta^2(219648405891600c^6 + 1340749967331915296b^3\delta^3 \\
& - 405700551347730324c^2b^2\delta^2 + 28069045277666659c^4b\delta) - 16ah\delta(441948502800c^8 + 344665585247955 52b^4\delta^4 \\
& - 13486645802756996c^2b^3\delta^3 + 1361828107371227c^4b^2\delta^2 - 30048250256353c^6b\delta) + 16h^2(3556929600c^{10} \\
& + 38816931803733248b^5\delta^5 - 12912400926867744c^2b^4\delta^4 + 1264785162770716c^4b^3\delta^3 - 24787550308409c^6b^2\delta^2 \\
& - 938216923796c^8b\delta)] \\
& \geqslant 0
\end{aligned}
$$

$$
\begin{aligned}
\pi_{mm} - \pi_{mc} = {} & \frac{b}{64(3328904b\delta - 247009c^2)(10b\delta - c^2)^2}[64a^2\delta^2(6126048b\delta - 11435c^2) - 16ah\delta(32817536b^2\delta^2 - 3277144c^2b\delta + 119773c^4) \\
& - h^2(228200448b^3\delta^3 - 79028544c^2b^2\delta^2 + 7890192c^4b\delta - 250981c^6)] \geqslant 0
\end{aligned}
$$

$$\pi_{mr}-\pi_{mc}=-\frac{b}{64(10b\delta-c^2)^2(402653184b^4\delta^4-65011712c^2b^3\delta^3+434176c^4b^2\delta^2+4224c^6b\delta-31c^8)^2}\Big[64a^2\delta^2(16010296675302113328b^8\delta^8-8012800938580377760c^2b^7\delta^7-175451c^{16}+133108252048097280c^4b^6\delta^6-7622820699832320c^6b^5\delta^5+28212759363584c^8b^4\delta^4+1848753160192c^{10}b^3\delta^3-24729638912c^{12}b^2\delta^2+114037704c^{14}b\delta)+16ah\delta(15763c^{18}-25940733853654056960b^9\delta^9+15316460857710346240c^2b^8\delta^8-3064064028704768000c^4b^7\delta^7+245109316816732160c^6b^6\delta^6-6992774498877440c^8b^5\delta^5+107895759831040c^{10}b^4\delta^4-129836969984c^{12}b^3\delta^3+1239697216c^{14}b^2\delta^2-6964048c^{16}b\delta)+h^2(4737c^{20}+68598829524107395072b^{10}\delta^{10}-36449883584123109376c^2b^9\delta^9+7189856067608641536c^4b^8\delta^8-630958733328908288c^6b^7\delta^7+21862880332742656c^8b^6\delta^6-78512312549376c^{10}b^5\delta^5-4549741117440c^{12}b^4\delta^4+53308955136c^{14}b^3\delta^3-80433808c^{16}b^2\delta^2-1274264c^{18}b\delta)\Big]$$

$\pi_{mr}-\pi_{mc}>0$ in the region bounded by $14.21\leqslant c\leq 15, 5\leqslant\delta<5.57$ and the curve $\Psi_4=0$; $\pi_{mr}-\pi_{mc}\leqslant 0$ for all other values of c and δ.

$$\pi_{mw}-\pi_{mc}=-\frac{1}{11999296b\delta^2(3844b\delta-497c^2)^2(10b\delta-c^2)^2}[32a^2\delta^2(30079504946704b^4\delta^4-15354779813980c^2b^3\delta^3+2368677631970c^4b^2\delta^2-889232400c^8-107835125251c^6b\delta)+16ah\delta(57254400c^{10}-5820315166464b^5\delta^5+9369225499696c^2b^4\delta^4-2276608396584c^4b^3\delta^3+180053716515c^6b^2\delta^2-4266227744c^8b\delta)+h^2(786935740571648b^6\delta^6-374489574401664c^2b^5\delta^5+64103378175888c^4b^4\delta^4-4507552531728c^6b^3\delta^3-7372800c^{12}+85660866629c^8b^2\delta^2+1992828928c^{10}b\delta)]$$

$\pi_{mw}-\pi_{mc}>0$ in the region bounded by $12.6\leqslant c\leq 15, 5\leqslant\delta<7.09$ and the curve $\Psi_5=0$; $\pi_{mw}-\pi_{mc}\leqslant 0$ for all other values of c and δ.

Appendix H. Proof of Proposition-4

$$\alpha_m-\alpha_r=\frac{c(c^2-128b\delta)[24576b^2\delta^2(2bh-5a)+c^4(31a+23bh)-64c^2b\delta(17a+36bh)]}{31c^8-402653184b^4\delta^4+65011712c^2b^3\delta^3-434176c^4b^2\delta^2-4224c^6b\delta}+\frac{c(247009a-53800bh)}{3328904b\delta-247009c^2}]\geqslant 0$$

$$\alpha_w-\alpha_r=\frac{c(c^2-128b\delta)[a(31c^4-122880b^2\delta^2-1088c^2b\delta)+bh(23c^4+49152b^2\delta^2-2304c^2b\delta)]}{31c^8-402653184b^4\delta^4+65011712c^2b^3\delta^3-434176c^4b^2\delta^2-4224c^6b\delta}-\frac{497ac\delta-232cbh\delta+8c^3h}{994c^2\delta-7688b\delta^2}\geqslant 0$$

$$\alpha_c-\alpha_m=-\frac{c(247009a-53800bh)}{3328904b\delta-247009c^2}-\frac{c(4a-bh)}{4(c^2-10b\delta)}\geqslant 0$$

$$\alpha_c-\alpha_w=\frac{16c^5h-c^3\delta(994a+127bh)+4cb\delta^2(1359a+199bh)}{4\delta(497c^2-3844b\delta)(c^2-10b\delta)}\geqslant 0$$

$$\alpha_w-\alpha_m=\frac{497ac\delta(247009c^2-492032b\delta)-8h(247009c^5+44836416cb^2\delta^2-3807515c^3b\delta)}{2\delta(3844b\delta-497c^2)(3328904b\delta-247009c^2)}$$

$\alpha_w-\alpha_m>0$ in the region bounded by $9.25\leqslant c\leq 15, 5\leqslant\delta<13.15$ and the curve $\Psi_6=0$; $\alpha_w-\alpha_m\leqslant 0$ for all other values of c and δ.

Appendix I. Proof of Proposition-5

$$Q_w-Q_m=\frac{c^2\left[\frac{2165(247009a-84552bh)}{3844b\delta-497c^2}+\frac{1199261(247009a-53800bh)}{247009c^2-3328904b\delta}-\frac{1984h}{\delta}\right]}{3812132}\geqslant 0$$

$$Q_r-Q_m=\frac{b}{4(402653184b^4\delta^4-65011712c^2b^3\delta^3+434176c^4b^2\delta^2+4224c^6b\delta-31c^8)}[(c^2-128b\delta)[64a\delta(c^4-49152b^2\delta^2+2176c^2b\delta)+h(3c^6+98304c^2b^2\delta^2-640c^4b\delta)]-\frac{62b(16891a\delta-4528bh\delta+63c^2h)}{3328904b\delta-247009c^2}$$

$Q_r-Q_m>0$ in the region bounded by $11.34\leqslant c\leq 15, 5\leqslant\delta<8.75$ and the curve $\Psi_7=0$; $Q_r-Q_m\leqslant 0$ for all other values of c and δ.

$$Q_r-Q_w=\frac{b(c^2-128b\delta)[64a\delta(c^4-49152b^2\delta^2+2176c^2b\delta)+h(3c^6+98304c^2b^2\delta^2-640c^4b\delta)]}{4(402653184b^4\delta^4-65011712c^2b^3\delta^3+434176c^4b^2\delta^2+4224c^6b\delta-31c^8)}-\frac{1}{433\delta(3844b\delta-497c^2)}[7a\delta(74803b\delta-994c^2)+2h(56c^4-70184b^2\delta^2-1755c^2b\delta)]$$

$Q_r-Q_w>0$ in the region bounded by $14.46<c\leq 15, 5\leqslant\delta<5.38$ and the curve $\Psi_8=0$; $Q_r-Q_w\leqslant 0$ for all other values of c and δ.

$$Q_c-Q_r=\frac{c^2bh-40ab\delta}{8c^2-80b\delta}-\frac{b(c^2-128b\delta)[64a\delta(c^4-49152b^2\delta^2+2176c^2b\delta)+h(3c^6+98304c^2b^2\delta^2-640c^4b\delta)]}{4(402653184b^4\delta^4-65011712c^2b^3\delta^3+434176c^4b^2\delta^2+4224c^6b\delta-31c^8)}ges0$$

$$Q_c - Q_w = \frac{c^2bh - 40ab\delta}{8c^2 - 80b\delta} - \frac{7a\delta(74803b\delta - 994c^2) + 2h(56c^4 - 70184b^2\delta^2 - 1755c^2b\delta)}{433\delta(3844b\delta - 497c^2)} \geqslant 0$$

Appendix J. Proof of Proposition-6

$$p_{1rr} - p_{1rw} = \frac{1}{4(402653184b^4\delta^4 - 65011712c^2b^3\delta^3 + 434176c^4b^2\delta^2 + 4224c^6b\delta - 31c^8)}$$
$$\left[256a\delta(5505024b^3\delta^3 - 741376c^2b^2\delta^2 + 6736c^4b\delta - 13c^6) + h(123c^8 - 402653184b^4\delta^4 + 47185920c^2b^3\delta^3 + 827392c^4b^2\delta^2 - 24896c^6b\delta)\right]$$
$$-\frac{a\delta(5864084b\delta - 438851c^2) + 8h(883c^4 - 145948b^2\delta^2 - 1623c^2b\delta)}{1732b\delta(3844b\delta - 497c^2)} \leqslant 0$$

$$p_{1rw} - p_{1rm} = -\frac{c^2[497a\delta(775575236b\delta - 218108947c^2) + 8h(218108947c^4 + 28783157388b^2\delta^2 - 2902599005c^2b\delta)]}{1732b\delta(3844b\delta - 497c^2)(3328904b\delta - 247009c^2)} \leqslant 0$$

$$p_{1rc} - p_{1rm} = \frac{2(bh\delta - 4a\delta)}{c^2 - 10b\delta} - \frac{583792bh\delta - 2932042a\delta + 4068c^2h}{247009c^2 - 3328904b\delta} \leqslant 0$$

$$p_{1rw} - p_{1rc} = \frac{a\delta(5864084b\delta - 438851c^2) + 8h(883c^4 - 145948b^2\delta^2 - 1623c^2b\delta)}{1732b\delta(3844b\delta - 497c^2)} - \frac{2(bh\delta - 4a\delta)}{c^2 - 10b\delta}$$

$p_{1rw} - p_{1rc} < 0$ in the region bounded by $9.83 \leqslant c \leq 15, 5 \leqslant \delta < 11.66$ and the curve $\Psi_9 = 0; p_{1rw} - p_{1rc} \geqslant 0$ for all other values of c and δ.

$$p_{1rr} - p_{1rc} = \frac{1}{4(402653184b^4\delta^4 - 65011712c^2b^3\delta^3 + 434176c^4b^2\delta^2 + 4224c^6b\delta - 31c^8)}$$
$$\left[256a\delta(5505024b^3\delta^3 - 741376c^2b^2\delta^2 + 6736c^4b\delta - 13c^6) + h(123c^8 - 402653184b^4\delta^4 + 47185920c^2b^3\delta^3 + 827392c^4b^2\delta^2 - 24896c^6b\delta)\right]$$
$$-\frac{2(bh\delta - 4a\delta)}{c^2 - 10b\delta}$$

$p_{1rr} - p_{1rc} < 0$ in the region bounded by $7.17 \leqslant c \leq 15, 5 \leqslant \delta < 21.9$ and the curve $\Psi_{10} = 0; p_{1rr} - p_{1rc} \geqslant 0$ for all other values of c and δ.

Appendix K. Proof of Proposition-7

$$p_{2rc} - p_{2rr} = \frac{1}{8(c^2 - 10b\delta)(31c^8 - 402653184b^4\delta^4 + 65011712c^2b^3\delta^3 - 434176c^4b^2\delta^2 - 4224c^6b\delta)}$$
$$\left[4194304c^2b^3\delta^4(679a + 61bh) - 805306368b^4\delta^5(7a + 2bh) - 16384c^4b^2\delta^3(23051a + 170bh) - 8c^8\delta(1065a + 5807bh)\right.$$
$$\left. + 256c^6b\delta^2(14853a + 10063bh) + 209c^{10}h\right] \leqslant 0$$

$$p_{2rc} - p_{2rw} = \frac{56a\delta + 16bh\delta - 3c^2h}{80b\delta - 8c^2} - \frac{a\delta(5357048b\delta - 394121c^2) + 8h(793c^4 + 216132b^2\delta^2 - 46850c^2b\delta)}{1732b\delta(3844b\delta - 497c^2)} \leqslant 0$$

$$p_{2rc} - p_{2rm} = \frac{56a\delta + 16bh\delta - 3c^2h}{80b\delta - 8c^2} - \frac{2(1339262a\delta + 432264bh\delta - 53719c^2h)}{3328904b\delta - 247009c^2} \leqslant 0$$

$$p_{2rr} - p_{2rm} = \frac{1}{805306368b^4\delta^4 - 130023424c^2b^3\delta^3 + 868352c^4b^2\delta^2 + 8448c^6b\delta - 62c^8}$$
$$\left[32a\delta(22020096b^3\delta^3 - 2867200c^2b^2\delta^2 + 27328c^4b\delta - 53c^6) + h(29c^8 + 201326592b^4\delta^4 - 42467328c^2b^3\delta^3 + 872448c^4b^2\delta^2 - 8032c^6b\delta)\right]$$
$$-\frac{2(1339262a\delta + 432264bh\delta - 53719c^2h)}{3328904b\delta - 247009c^2}$$

$p_{2rr} - p_{2rm} < 0$ in the region bounded by $10.55 \leqslant c \leq 15, 5 \leqslant \delta < 10.12$ and the curve $\Psi_{11}; p_{2rr} - p_{2rm} \geqslant 0$ for all other values of c and δ.

$$p_{2rr} - p_{2rw} = \frac{1}{805306368b^4\delta^4 - 130023424c^2b^3\delta^3 + 868352c^4b^2\delta^2 + 8448c^6b\delta - 62c^8}\left[32a\delta(22020096b^3\delta^3 - 2867200c^2b^2\delta^2 + 27328c^4b\delta - 53c^6)\right.$$
$$\left. + h(29c^8 + 201326592b^4\delta^4 - 42467328c^2b^3\delta^3 + 872448c^4b^2\delta^2 - 8032c^6b\delta)\right]$$
$$-\frac{a\delta(5357048b\delta - 394121c^2) + 8h(793c^4 + 216132b^2\delta^2 - 46850c^2b\delta)}{1732b\delta(3844b\delta - 497c^2)}$$

$p_{2rr} - p_{2rw} < 0$ in the region bounded by $12.23 < c \leq 15, 5 \leqslant \delta < 7.52$ and the curve $\Psi_{12} = 0; p_{2rr} - p_{2rw} \geqslant 0$ for all other values of c and δ.

$$p_{2rm} - p_{2rw} = \frac{c^2[497a\delta(663070160b\delta - 195878137c^2) + 8h(195878137c^4 + 26909359536b^2\delta^2 - 2651810003c^2b\delta)]}{1732b\delta(3844b\delta - 497c^2)(3328904b\delta - 247009c^2)}$$

$p_{2rm} - p_{2rw} < 0$ in the region bounded by $12.02 \leqslant c \leq 15, 5 \leqslant \delta < 7.79$ and the curve $\Psi_{13} = 0; p_{2rm} - p_{2rw} \geqslant 0$ for all other values of c and δ.

Appendix L. Proof of Proposition-8

$$p_{2rm} - p_{1rm} = \frac{2(126759a\delta - 724160bh\delta + 51685c^2h)}{247009c^2 - 3328904b\delta} \leqslant 0$$

$$p_{2rw} - p_{1rw} = \frac{3a\delta(7455c^2 - 84506b\delta) - 4h(90c^4 - 362080b^2\delta^2 + 45227c^2b\delta)}{866b\delta(3844b\delta - 497c^2)} \leqslant 0$$

$$p_{1rr} - p_{2rr} = \frac{64ac^2\delta(c^4 - 98304b^2\delta^2 - 384c^2b\delta) + h(65c^8 - 805306368b^4\delta^4 + 132120576c^2b^3\delta^3 - 917504c^4b^2\delta^2 - 8832c^6b\delta)}{4(402653184b^4\delta^4 - 65011712c^2b^3\delta^3 + 434176c^4b^2\delta^2 + 4224c^6b\delta - 31c^8)} \leqslant 0$$

$$p_{2rc} - p_{1rc} = \frac{8a\delta - 32bh\delta + 3c^2h}{8c^2 - 80b\delta} \leqslant 0$$

Appendix M. Proof of Proposition-9

$$I_w - I_m = \frac{c^2\left[497a\delta(386977216b\delta - 11609423c^2) + 8h\left(11609423c^4 - 9420579584b^2\delta^2 + 311112651c^2b\delta\right)\right]}{1732\delta(3844b\delta - 497c^2)(3328904b\delta - 247009c^2)} \geqslant 0$$

$$I_c - I_m = \frac{b(8a\delta - 32bh\delta + 3c^2h)}{8(10b\delta - c^2)} - \frac{4b(78089a\delta - 288176bh\delta + 20121c^2h)}{3328904b\delta - 247009c^2} \geqslant 0$$

$$I_w - I_c = \frac{a\delta(23359c^2 + 624712b\delta) - 8h\left(47c^4 + 288176b^2\delta^2 - 33167c^2b\delta\right)}{1732\delta(3844b\delta - 497c^2)} - \frac{b(8a\delta - 32bh\delta + 3c^2h)}{8(10b\delta - c^2)} \geqslant 0$$

$I_w - I_c > 0$ in the region bounded by $6.05 \leqslant c \leq 15, 5 \leqslant \delta \leq 25$ and the curve $\Psi_{14} = 0; I_w - I_c \leqslant 0$ for all other values of c and δ.

$$I_r - I_m = \frac{b\left[64ac^2\delta\left(5c^4 + 114688b^2\delta^2 - 1792c^2b\delta\right) + h\left(c^2 - 128b\delta\right)^2\left(15c^4 - 16384b^2\delta^2 + 2304c^2b\delta\right)\right]}{805306368b^4\delta^4 - 130023424c^2b^3\delta^3 + 868352c^4b^2\delta^2 + 8448c^6b\delta - 62c^8} - \frac{4b(78089a\delta - 288176bh\delta + 20121c^2h)}{3328904b\delta - 247009c^2}$$

$I_r - I_m > 0$ in the region bounded by $14.05 < c \leq 15, 5 \leqslant \delta < 7$ and the curve $\Psi_{15} = 0; I_r - I_m \leqslant 0$ for all other values of c and δ.

$$I_r - I_c = \frac{b\left[64ac^2\delta\left(5c^4 + 114688b^2\delta^2 - 1792c^2b\delta\right) + h\left(c^2 - 128b\delta\right)^2\left(15c^4 - 16384b^2\delta^2 + 2304c^2b\delta\right)\right]}{805306368b^4\delta^4 - 130023424c^2b^3\delta^3 + 868352c^4b^2\delta^2 + 8448c^6b\delta - 62c^8} - \frac{b(8a\delta - 32bh\delta + 3c^2h)}{8(10b\delta - c^2)}$$

$I_r - I_c > 0$ in the region bounded by $14.68 \leqslant c \leq 15, 5 \leqslant \delta \leq 5.22$ and the curve $\Psi_{16} = 0; I_r - I_c \leqslant 0$ for all other values of c and δ.

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