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Research Article

Complementary Product Pricing and Service Cooperation Strategy in a Dual-Channel Supply Chain

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This paper investigates a pricing game and service cooperation for complementary products in a dual-channel supply chain composed of two manufacturers and one retailer. The products of the two manufacturers are complementary products. One manufacturer sells products simultaneously through its own online channel and the traditional retailer, and the manufacturer delivers the product's service to the retailer in its network direct sales channel by cooperating with the retailer in the form of service cost sharing. Considering the different market power structures of channel members, we establish three different pricing game models. By using the backward induction method and game theory, we obtain the corresponding analytical equilibrium solutions. Then, the service cooperation strategy of using the channel service sensitivity coefficients to construct the weight to share the service cost is proposed. Finally, numerical examples of optimal pricing strategies and profit conditions in different game situations are given, and sensitivity analysis of some key parameters is selectively performed, in which some valuable management insights are obtained.

1. Introduction

With the continuous development and popularization of Internet technology, increasing people are turning to online channels to purchase goods and e-commerce shopping methods are gaining popularity in the retail industry. Manufacturers such as Apple, IBM, DELL, Hewett-Packard, Nike, and Sony [1] are increasingly marketing their products not only through brick-and-mortar retailers (referred to as the traditional retail channel) but also through an online channel (referred to as a direct channel), i.e., leveraging dual channels: a direct online channel and a traditional retail channel [2–4]. The role of this dual-channel sales model in business activities and consumers is growing. On the one hand, it provides unprecedented opportunities for manufacturers or retailers who adopt the dual-channel business strategy to easily reach out and understand a wider range of consumers, meet the needs of consumers for multichannel shopping, improve consumer loyalty and satisfaction, and ultimately increase demand and revenue. On the other hand, this dual-channel sales mode can also provide greater convenience and choices to consumers. For example, consumers can choose to experience products in the physical stores of traditional retailers or go to online sales channels to obtain relevant information about the products before deciding whether to buy and which channel to use.

While the dual-channel provides income for business entities and benefits to consumers, there are also some negative problems. First, manufacturers selling products directly through online channels will seriously erode the market share and profits of traditional retailers, and the incompatibility of the two parties' goals will lead to channel conflicts. Compared with the manufacturer's online channel, the offline retail channel of the traditional retailer is geographically closer to the customer and has an advantage in providing customers with good presales service (function introduction and trial experience) and convenient after-sales service. However, the products sold in the manufacturer's network are manufactured by the manufacturer itself, there is no other intermediate link, and the network has a greater cost advantage. Therefore, the product pricing of the manufacturer's online channel is often lower than the traditional offline channel in obtaining the price competitive advantage. For customers, on the one hand, they hope to enjoy presales services to deepen their understanding of products, and on the other hand, they are eager to buy products at a lower price. Thus, first visiting the physical store of the traditional retailer's offline channel to enjoy the presales service and then switching to the manufacturer's online channel for purchase seems to be a good choice for the customer, exemplifying the customer's free-riding behaviour for the traditional retail service and damage to its interests. For certain goods, such as clothing, shoes, bags, furniture, and children's toys, among others [5], presales services can be separated from actual sales [6], and the customer's free-rider phenomenon occurs often, which will not only reduce the market share of traditional retailers' offline channels but also deprive traditional retailers of their willingness to provide quality services. Second, the development of manufacturers' network channels may lead to a significant increase in the number of consumer returns. According to Mostard and Teunter [7] and Akcay et al. [8], the return rate of offline traditional channels is approximately 35%, whereas the return rate of online channels is as high as 75%. Thus, compared with traditional retail channels, product return is an important part of the business process of the network channel. The main reason for this result is the difference between the services provided by the network channel and those of the traditional retail channel. A considerable number of online consumers may not have the opportunity or find it inconvenient to go to traditional retailers to enjoy presales services including function introduction and trial experience before purchase and then may return goods due to dissatisfaction. Many consumers directly return products purchased through the network channel due to the difference in the convenience of after-sales service between channels and then transfer to offline physical retailers for purchase.

A strategy in which manufacturers sell products to customers simultaneously through dual channels composed of a traditional retail channel and a network channel will have different aspects and degrees of impact on all parties in the supply chain, both positive and negative. However, due to the fierce competition situation and the needs of consumers for multichannel shopping, it is a general trend for most manufacturers or retailers to establish a dual-channel supply chain model based on traditional channels. Therefore, it is necessary to discuss the following questions arising from the dual-channel supply chain model in depth: can appropriate strategies be designed to mitigate competition and conflict between channels? How should channel members set their channel prices to maximize their profits when selling products through the dual channel? What kind of market power structure is beneficial to all dual-channel members? What strategies should the traditional retailer adopt to avoid the free-riding behaviour of online consumers? Can manufacturers design appropriate strategies to remedy the weakness of their network channel services? Given the increasingly prominent position of the dual-channel supply chain in the continuous evolution of the business environment in recent years, research on the dual-channel supply chain has attracted the attention of many scholars. Experts and scholars have discussed the dual-channel supply chain from different perspectives and proposed many effective mechanisms to eliminate or alleviate the competition and conflict between the dual channels, including price competition [9–13], channel conflict and coordination mechanisms [14–17], pricing decisions [10, 18–20], and service competition and cooperation [18, 21–23].

However, most of these studies focused on dual-channel supply chains consider only a single product (a homogeneous, replaceable product), and there are few studies on pricing and service issues for complementary products in a dual-channel supply chain environment. Complementary products mean that there is a certain kind of consumption dependence between various products, and a variety of products can match each other to meet customer needs or realize the full utility of the product; examples of such products include tires and wheels, toothpaste and toothbrushes, badminton and badminton rackets, and pencils and erasers, among others. The marketing model for complementary products is different from that for alternative products because complementary products benefit from each other's sales rather than damaging each other's sales, and they can be considered bundled together [24]. According to the theory of cross-elasticity, the demand for a product and the price of its complementary product change in the opposite direction. The price fluctuation of a complementary product will stimulate a change in the need for the other product and achieve mutual promotion. As a result, retailers selling complementary products in the same market are interrelated, and a retailer's marketing campaign aimed at increasing the penetration of its product market will also have a positive impact on complementary products. In a dual-channel supply chain system in which the manufacturer develops the network channel to directly sell products, when the upstream manufacturer sells the same type of products through the network channel, a traditional retailer can choose to sell the complementary products of the product simultaneously in its offline physical stores. The advantages that the traditional retailer can gain by selling complementary products are obvious. On the one hand, the sales of complementary products will generate new demand, thus increasing the revenue of the traditional retailer; on the other hand, the existence of complementary products may turn some online consumers who are free riders into potential customers, thereby reducing the cannibalization of the traditional retailer's market share by the manufacturer's online channel and enhancing its competitiveness. Of course, whether the above advantages can be obtained is also related to the product channel pricing and the service level provided by the retailer. Although the manufacturer can attract consumers to buy from its network channel at low prices by virtue of the cost advantages, problems such as returns caused by lack of presales experience or after-sales services will make it difficult for the manufacturer to achieve the expected benefits in network channel sales, especially after the retailer chooses to sell complementary products simultaneously. Therefore, ensuring the service quality of the manufacturer's online channel is key to maintaining low returns and consumer loyalty. However, in existing research on the dual-channel supply chain system, there are few studies of the above situation. Accordingly, this paper studies the pricing game and service cooperation of complementary products in a dual-channel supply chain system composed of two manufacturers and one retailer. Specifically, we study the following problems of the whole process, in which two manufacturers of complementary products wholesale their products to the same retailer and one of the two manufacturers breaks a direct network channel to sell its products:

(1) What is the optimal channel pricing strategy of each channel member in the sales process of complementary products in the above dual-channel supply chain?

(2) Which market power structure is more beneficial to channel members? What is the system performance of channel members under different power structures?

(3) How can the manufacturer with dual channels cooperate with the retailer to ensure the service quality level of its network channel and benefit both sides?

(4) How do other key parameters of the system affect pricing decisions and profits of channel members under different power structures?

To answer the above questions, we establish three game models according to the difference in market power structure between two manufacturers and one retailer: (1) a Bertrand model of the simultaneous action of two manufacturers as leaders; (2) a Stackelberg model in which the manufacturer of product 1 acts as the leader and the manufacturer of product 2 acts as a follower; (3) contrary to (2), a Stackelberg model in which the manufacturer of product 2 acts as the leader and the manufacturer of product 1 acts as the follower. It should be noted that, in the above three situations, the retailer always acts as the follower. In addition, the manufacturer with a dual-channel competes with the retailer in the demand market, which may lead to some negative effects, such as channel conflicts and free-riding behaviour, and will damage the profits of all parties and the overall performance of the supply chain. In order to avoid this situation and encourage the traditional retailer to maintain a high level of service in a dual-channel environment, we propose a win-win strategy for the dual-channel manufacturer to achieve service cooperation with the retailer through a service cost-sharing contract.

The rest of this article is organized as follows: in Section 2, we review the relevant literature; Section 3 introduces the model framework and gives the problem description and symbols; Section 4 provides the model analysis, where the pricing game model under three different supply chain power structures is established, and the corresponding equilibrium solutions are obtained; in Section 5, some sensitivity analyses of the key parameters of the equilibrium solutions are carried out through numerical examples, and the optimal pricing strategies and profits are compared to provide insights for management. The conclusions are presented in the last section.

2. Literature Review

This paper proposes a framework that involves the issues of product complementarity, a dual-channel supply chain, and service cooperation simultaneously and is an intersection of multiple research areas. Two streams of the literature are relevant to our research: the first examines dual-channel supply chain systems, and the second discusses service strategies of the dual-channel supply chain. Now we briefly review the literature from these two aspects.

In the first stream, experts and scholars have carried out various studies on the dual-channel supply chain system from different angles and have achieved fruitful results. Most of these studies can be divided into two types depending on the structure of the dual-channel supply chain system: the manufacturer-retailer setting and the dual-channel retailer setting. The manufacturer-retailer setting generally involves a channel structure in which the manufacturer owns both offline and online channels while the retailer only manages the offline retail channel; that is, a system where the manufacturer simultaneously sells a single product to customers through its own online store and an independent retailer. The online channel and offline channel under this setting belong to different stakeholders, and the inconsistency of their respective goals will lead to competition and conflict between channels. Research on the dual-channel supply chain system under this setting mainly focuses on various competitions caused by channel conflicts and related mitigation strategies. The types of channel competition include price competition [9–11, 13], service competition [18, 21, 22], and competition in product orders [25–27]. Manufacturers open up online channels to sell the same products as retailer offline channels, and channel conflicts and price competition are inevitable. Chiang et al. [10] showed that manufacturers can reduce profit losses by introducing online channels, but this will cause retailers to lower retail prices to stimulate demand from offline channels, thereby damaging retailers' profits. Park and Keh [28] studied the dual-channel pricing equilibrium when the demand was determined only by the price, in which the manufacturer opens up the network channel as the leader or the traditional retailer does so as the leader. They compared the profits of supply between the dual channel and the single traditional channel, and the results showed that both the profit of the manufacturer and the overall profit of the supply chain increased in the dual channel, but the profit of the traditional retailer decreased. Balakrishnan et al. [9] studied the "showrooming" behaviour of consumers who first visit physical retail stores and then choose to switch to e-retailers to buy goods at a lower price. They related this behaviour to a decrease in profits of the physical retailer and showed that consumers' browsing and switching will intensify channel competition and reduce the profits of the two retailers. Some scholars hold different views, such as Arya et al. [11], who studied the pricing equilibrium of a manufacturer and a traditional retailer before and after a manufacturer establishes an online direct channel. They found that manufacturer tends to lower the wholesale price in order to avoid a decline in wholesale income due to the sharp decline in sales of traditional retail channel, which can partially eliminate the double marginal effect of a single traditional channel and simultaneously benefit both the manufacturer and the traditional retailer. Hua et al. [29] and Shao [12] also hold the same view. Thus, to some extent, competition can have a stimulus effect that positively impacts both sides of the competition.

However, when selling single or similar products in a decentralized system with more than one retail channel, each channel is in fact trying to maximize its own profits, which will inevitably lead to competition in many of the aspects discussed above [4, 15, 30]. Our focus is how to weaken the negative effects of competition in this process while simultaneously strengthening its positive impact to benefit from it. In this vein, numerous channel cooperation and coordination mechanisms aimed at alleviating various competitions and conflicts have been developed, including cooperative pricing [18, 19, 31, 32], service cooperation [23, 33], and other coordination strategies [16, 17, 34]. Dumrongsiri et al. [18] studied the equilibrium conditions of the market shares of the manufacturer and the retailer in the dual-channel supply chain and showed that the marginal cost difference between the two channels plays an important role in determining the existence of dual-channel equilibrium. In a dual-channel supply chain system in which a manufacturer sells the same product through two competitive retailers, Chen [19] studied the influence of the channel strategy and channel form selection on the profits of all parties and the whole system. Ren et al. [31] considered the equilibrium pricing of the decentralized decision-making mode and the centralized decision-making mode of the dual-channel supply chain in the case of customer returns. The research showed that the total profit of the dual-channel supply chain under the decentralized decision-making mode will be lower than the total profit under the centralized decision-making mode, and a new cooperation mechanism is designed to coordinate the conflicts under the decentralized decision-making mode to achieve a win-win situation for both manufacturers and retailers. Xu et al. [23] studied the effect of price comparison services on pricing strategies in the dual-channel supply chain. Zhou et al. [33] studied the pricing and service strategies when the manufacturer's online channel free-rides the retailer's presales services by sharing the retailer's sales effort cost. Cao et al. [16] discussed the impact of the simultaneous disruption of production cost and demand on revenue-sharing contracts and provided the coordination mechanism between the disruption and the optimal strategy of the participants. In contrast to the manufacturer-retailer setting, where the online channel and the offline channel belong to different stakeholders, under the dual-channel retailer setting, as the sole decision-maker of the system retail channel, the retailer operates both online and offline sales channels. There are many papers about the dual-channel supply chain system under this setting. Yan [35] constructed a game theory model framework to help enterprises with mixed online and traditional retail channels finding the best pricing strategy and market structure. According to Yan et al. [36], the creation of an e-commerce channel by an entity company that operates completely independently of existing physical channels will lead to fierce channel conflicts, while channel integration with profit sharing can eliminate channel conflicts and improve the channel coordination of the multichannel company. Zhang [37] studied the multichannel and price advertising strategies of the retailer and answered the questions of when the traditional entity retailer should adopt a multichannel strategy and when the multichannel retailer should use its network channel to promote offline prices. Yan [38] developed a game-theoretic model to determine the best brand strategy and market structure for a dual-channel retailer. The results showed that, for a dual-channel retailer, the best brand strategy is to adopt as many brand differences as possible between the online and offline stores, especially when consumers are less price sensitive and the market base is larger. With the progress of network technology and the development of e-commerce, more and more retailers are adopting the dual-channel management strategy to increase demands and revenue, and scholars have carried out numerous studies on decision-making problems in the dual-channel retailer setting, including channel pricing [35, 39], channel coordination [36, 40–42], and channel strategies [37, 38, 43–46]. Li [39] studied the inventory-sharing and pricing strategy of a dual-channel retailer relative to channel preference and proposed a strategy of sharing inventory and dynamic pricing. Abhishek et al. [41] studied the retailer's channel selection and showed that as long as network channel sales have a negative impact on demand via the traditional channel, the retailer is more inclined to use agency sales. By contrast, when network channel sales greatly simulate traditional channel demand, the retailer is more inclined to sign a resale contract with the manufacturer. Zhang and Wang [40] studied how a dual-channel retailer selling short-life cycle products could coordinate the two channels through the combination of an appropriate pricing strategy and channel. Gallino and Moreno [43] studied the impact of the strategy of preordering online and picking up in-store on the online and offline sales of a dual-channel retailer through empirical analysis and found that the implementation of this strategy can improve the sales and pedestrian volume of offline stores but has a negative impact on online sales. Wang et al. [44] studied the influence of the channel operation cost on the channel selection and pricing strategy of a dual-channel retailer and found that the difference between the online and offline channel operation costs is very important in the retailer's selection of channel strategy. Zhang et al. [45] studied the choice of the retailer's channel structure—online channel, offline channel, or dual channel. In addition, scholars [47, 48] have studied the pricing and replenishment strategies of the dual-channel supply chain system, the pricing- and delivery time-dependent stochastic demands, etc. Although the present paper examines the dual-channel supply chain system, it is significantly different from the above research in terms of system structure and channel product type in the following two aspects. First, the dual-channel supply chain structure of this paper is set as two independent manufacturers and one retailer. Most existing research on dual-channel supply chain systems has been carried out under the single-manufacturer and single-retailer setting or the single dual-channel retailer setting. However, in practice, it is more common for the same retailer to sell products from multiple manufacturers simultaneously. Second, the channel products discussed in this paper are complementary products from different manufacturers. Many studies on dual-channel supply chain operation management (channel selection, pricing, and coordination) focus mostly on single products or alternative products and less on complementary products. In fact, as we noted above, in practice, a retailer may simultaneously sell products from multiple manufacturers that are complementary in function, such as spectacle lenses and spectacle frames. The relationship between price and demand is different for complementary products than for similar or alternative products, and these differences have received little attention in the literature. Thus, the research in this paper is of theoretical and practical significance.

The second literature stream mainly discusses the influence of service strategy on decision-making in the dual-channel supply chain. Customers are increasingly using service levels as the main measure in product selection; the impact of service levels on customer choices is even greater than that of price fluctuations. This phenomenon has led many researchers to focus on services. For example, Dumrongsiri et al. [18] studied the dual-channel supply chain in service and price competition and analysed the impacts of different products, costs, or service characteristics on the supply chain equilibrium behaviour. Yan and Pei [24] studied the impact of a direct sales channel on retailer service levels and found that new direct sales channels can reduce retailers' wholesale prices and increase sales and indicated that retail services have a significant impact on customer channel selection, demand, and loyalty. Dan et al. [14] studied retailers' optimal service and pricing strategies in noncooperative situations in a dual-channel supply chain and found that retail services greatly affected retailers and manufacturers' pricing strategies, such that increases in the customer demand ratio and customer loyalty will help improve the retailer's service level. Dan et al. [22] examined the impact of two-way free riding and service competition on member decisions by comparing the optimal service levels of the single-channel supply chain and the dual-channel supply chain. The results showed that when new channels are added, retailers always improve service levels to compete with manufacturers, while manufacturers need to consider their relationship with retailers and decide whether to increase or decrease their service levels. Ding et al. [49] studied service competition in the network duopoly market in the context of inventory and environmental constraints. Most of the above papers studied the relevant strategies in the dual-channel supply chain at the level of service competition, but the study of this topic is not limited to these papers. Although the various decision-making schemes under the service competition strategy help improve the performance of the supply chain, the system efficiency loss is still large, especially when the traditional retail channels provide services, which will cause the free-riding phenomenon among the customers in network channels [33, 50–56]. With the deepening of research, some scholars have proposed that service cooperation strategies have better performance in avoiding channel conflicts and maximizing supply chain performance. Therefore, the decision-making optimization research on the dual-channel supply chain based on a service cooperation strategy is gradually deepening. Yao et al. [57] established a three-level game model of a supply chain composed of one manufacturer and two retailers and gave the conditions required for retailers and the manufacturer to cooperate on value-added service information. Unlike Yao et al. [57], Mukhopadhyay et al. [58] investigated a multichannel supply chain led by the manufacturer in which the manufacturer does not fully understand retailers' service information and gave the conditions required for retailers and the manufacturer to share information. Xu et al. [23] studied the impact of services on manufacturer and retailer pricing strategies in a dual-channel supply chain cooperative environment. The results showed that an excessive service level is uneconomical for both parties, and the manufacturer and retailer prefer to reduce prices and avoid improving service quality. In the context of the dual-channel supply chain, Chen [59] constructed a pricing game model in which the manufacturer shares the retailer's advertising expenses and determined product channel pricing and advertising cooperation strategies under the framework of the manufacturer Stackelberg model. Radhi and Zhang [60] studied the issue of return service cooperation between a dual-channel retailer online store and offline store and gave the pricing strategy for customers who purchase online products that can be returned to offline stores across channels. Zhou et al. [33] studied the pricing and service strategy issues of a dual-channel supply chain in which the manufacturer's online channel free rides the retailer's presales services by offering a service cost-sharing contract. Similar to the above literature, this paper also adopts the service strategy as a significant aspect of the differences between online and offline channels and considers the service cooperation strategy between channels. However, due to the particularities of the supply chain system structure and the complementarity of channel products, the form of cooperation of the service strategy and its influence on channel members will be different in this paper from the above literature. The structure setting of the supply chain system in this paper is two manufacturers and one retailer, and the products produced by the two manufacturers are complementary. The service cooperation strategy is only carried out between the retailer and one manufacturer, while the other manufacturer benefits from the service cooperation but does not share the service cost. There are many such cases in practice. For example, businesses provide services for electric toothbrushes but not for toothpaste; similar examples include cars and gasoline, printers, and ink cartridges.

As we stated in the last part of the discussion of the first stream of the literature, few studies have discussed decisions related to complementary products. For example, Yue et al. [61] indicated that the concept of complementary products emerges when customers need to purchase multiple products at the same time to obtain the full utility of the product. They also built a profit maximization model to obtain an optimal pricing strategy in which two complementary products that customers need to purchase were provided by two different companies. Sinitsyn [62] studied the price promotion coordination strategies of two types of complementary products for two competitive companies considering customer choice behaviours. Wei et al. [63] studied the pricing of two complementary products in a two-level supply chain by considering the different power structures of channel members. The above studies only examine decision-making for complementary products under the single-channel mode and do not include the cross-influence of different channel modes. As an extension of Wei et al. [63], Zhao et al. [64] studied the pricing of complementary products in a dual-channel supply chain consisting of two manufacturers and one retailer, in which one of the manufacturers distributes products through both the direct online channel and the traditional retail channel. By considering the different power structures of channel members, four pricing game models are established, and the corresponding optimal pricing strategies are given, but no discussion of services is involved. Furthermore, Wang et al. [65] studied the pricing and service decisions of complementary products in the context of a dual-channel supply chain. The difference is that they simply considered the retailer's service strategy and did not include service cooperation. The present paper also studies the pricing and service decisions of complementary products in a dual-channel supply chain consisting of two manufacturers and one retailer. However, unlike previous studies, this paper not only pays attention to the optimal channel pricing of each supply chain member under this setting but also focuses on how to formulate a service cooperation strategy between the manufacturer that establishes an online direct sales channel and the retailer that encourages the retailer to maintain a high level of service in the presence of service free-riders. The work in this paper enriches research on complementary product sales theory and service operation under the background of dual channels and has great significance for the operation of the dual-channel supply chain.

3. Problem Description and Model

This paper considers a two-stage supply chain with two manufacturers (marked M_1 and M_2) and a retailer (marked R). Manufacturer M_1 produces product 1 at a unit cost c_1 and distributes it to the retailer at wholesale price w_1. Meanwhile, manufacturer M_2 produces the product 2 at a unit cost c_2 and distributes the product 2 to the same retailer at wholesale price w_2. Then, the retailer then sells the two products to the final customer at retail prices p_1 and p_2, which satisfy $0 < c_1 < w_1 < p_1$ and $0 < c_2 < w_2 < p_2$, respectively. Product 1 and product 2 are functionally complementary products. In addition, manufacturer M_1 establishes a network direct channel to the consumer at direct sales price p_0 while supplying the retailer (the supply chain framework structure is shown in Figure 1). The retailer provides related services for product 1, and manufacturer M_1 cooperates with the retailer by sharing the service cost; that is, manufacturer M_1 entrusts the retailer with the relevant services of its direct channel product 1 and shares the service cost with the retailer proportionally. Since product 1 is serviced by the retailer in both the direct and retail channel, the service level of the two channels for product 1 can be considered the same, as denoted by s.

Similar to many studies (such as Chiang et al. [10], Zhou et al. [33], Zhao et al. [64], and Wang et al. [65]), to simplify the model and avoid mathematical complexity, we assume that the demand of the two channels is deterministic, with a linear demand function of the sale prices and service level of the products. Other forms of demand functions, such as the uncertain demand function that considers uncertainty in demand and the nonlinear demand function in which there is a nonlinear relationship between the demand and the prices and service level, potentially require more technical skill. In this paper, let D_0 denote consumer demand for product 1 through the direct sales channel, let D_1 denote consumer demand for product 1 through the retail channel, and let D_2 denote consumer demand for product 2. The corresponding demand functions can be expressed as follows:

$$D_0 = a_0 - k_1 p_0 + \delta p_1 - \gamma_1 p_2 + \theta_0 s, \tag{1}$$

$$D_1 = a_1 - k_1 p_1 + \delta p_0 - \gamma_2 p_2 + \theta_1 s, \tag{2}$$

$$D_2 = a_2 - k_2 p_2 - \gamma_1 p_0 - \gamma_2 p_1 + \theta_1 s, \tag{3}$$

where a_0 represents the primary market base of product 1 through the direct sales channel, a_1 represents the primary market base of product 1 through the traditional retail channel, and a_2 denotes the primary market base of product 2 through the traditional retail channel. Parameter k_1 denotes the self-price sensitivity of product 1's demand in both the direct channel and the traditional retail channel, k_2 denotes the self-price sensitivity of product 2's demand in the traditional retail channel, and δ is the cross-price sensitivity coefficient of product 1. It should be pointed out that when the same product is sold in different channels, the self-price sensitivity coefficient and cross-price sensitivity coefficient of channels are symmetric, which means that different channels have the same self-price sensitivity coefficient and cross-price sensitivity coefficient [29, 66]. Parameter γ_1 is the complementarity level between product 1 in the direct channel and product 2 in the traditional retail channel, and γ_2 denotes the complementarity level between products 1 and 2 in the traditional retail channel. θ_0 and θ_1 are the service sensitivity coefficients of the demand in the direct channel and traditional retail channel, respectively. Considering the functional complementarity between product 2 and product 1, it is reasonable to assume that product 2 enjoys the same demand service sensitivity

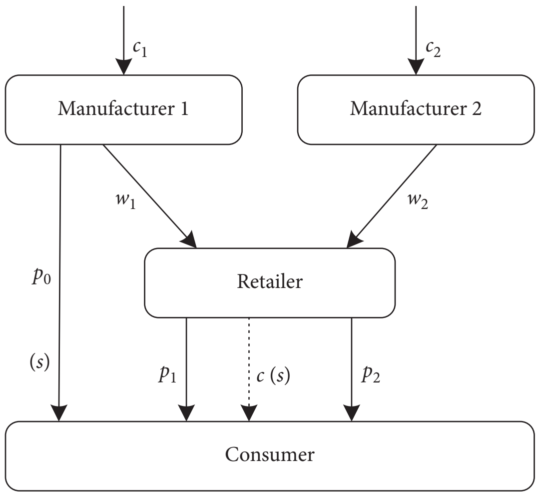

Figure 1: Dual-channel supply chain framework.

coefficient as product 1 in the traditional retail channel. The parameter k_i $(i = 1, 2)$ is always larger than other parameters $\delta, \gamma_1, \gamma_2$ and θ_j $(j = 0, 1)$; that is, the self-price sensitivity is greater than the cross-price sensitivity and the service sensitivity. As mentioned earlier, manufacturer M_1 and the retailer provide related services for product 1, and the demand for product 1 will increase. Since product 2 and product 1 are complementary products, the combination of the two customers can achieve the desired effect, so the demand for product 2 will be affected by that for product 1. When the demand for product 1 increases due to the provision of services, the demand for product 2 also increases, but manufacturer M_2 does not need to share the service cost. We consider using product 1's service sensitivity coefficient in the two channels to determine the allocation ratio to achieve service cooperation between manufacturer M_1 and the retailer, and the ratio of service cost that manufacturer M_1 apportionment is $\theta_0/\theta_0 + \theta_1$, while the retailer's ratio is $1 - (\theta_0/\theta_0 + \theta_1) = (\theta_1/\theta_0 + \theta_1)$. Suppose that the service cost generated by the retailer providing service for product 1 can be set as a strict convex function of the service level s and is given by $c(s) = (\mu/2)s^2$, where $\mu(>0)$ is the service cost coefficient. This assumption has been employed in the previous literature by many researchers, such as Yan and Pei [24], Dan et al. [14], Wang et al. [65], and Zhou et al. [33]. Thus, the profit functions of both the manufacturer and the retailer are, respectively, given as follows:

$$\prod_{M_1}(p_0, w_1) = (p_0 - c_1)(D_0 + (w_1 - c_1))D_1 - \frac{\mu\theta_0 s^2}{2(\theta_0 + \theta_1)}, \tag{4}$$

$$\prod_{M_2}(w_2) = (w_2 - c_2)D_2, \tag{5}$$

$$\prod_{R}(p_1, p_2) = (p_1 - w_1)D_1 + (p_2 - w_2)D_2 - \frac{\mu\theta_1 s^2}{2(\theta_0 + \theta_1)}. \tag{6}$$

To make the expression clearer and easier to read, we sorted the notations used in this paper and summarize them in Table 1.

According to the real economic significance of the variables, we implement the following assumptions about costs and prices, sensitivity coefficients of prices and services, and the complementarity level.

Assumption 1. For costs and prices, $0 < c_1 < w_1 < p_1$ and $0 < c_2 < w_2 < p_2$.

Assumption 2. For the sensitivity coefficients of prices and services, as well as the complementarity level, we assume that parameter k_i $(i = 1, 2)$ is always larger than parameters $\delta, \gamma_1, \gamma_2$ and θ_j $(j = 0, 1)$; that is, the self-price sensitivity is greater than the cross-price sensitivity and the service sensitivity. This is because the changes in the product in terms of its own retail price should have a greater impact compared to changes in other products or other channels.

In addition, to ensure that various profit expressions perform well and have unique optimality, the following additional conditions are added in this paper:

(i) $2k_1^3k_2 - 2k_1^2\gamma_2^2 - \gamma_1^2k_1^2 - 2\delta^2k_1k_2 - 2\delta\gamma_1\gamma_2k_1 + \delta^2\gamma_2^2 > 0$

(ii) $k_1k_2(4k_1^2k_2 - 6k_1\gamma_2^2 - 6\delta\gamma_1\gamma_2 - 3k_1\gamma_1^2 - 4\delta^2k_2) + \gamma_2^2(3\delta^2k_2 + 2k_1\gamma_1^2 + 4\delta\gamma_1\gamma_2 + 2k_1\gamma_2^2) > 0$

4. Model Analysis

Consider the sequential noncooperative game between two manufacturers and the retailer, where the two manufacturers are the leaders and the retailer is the follower. Depending on the sequence of decisions, there are three game situations between the two manufacturers: (i) $M_1 - M_2$ Bertrand game, i.e., manufacturer M_1 and manufacturer M_2 move simultaneously; (ii) $M_1 - M_2$ Stackelberg game, i.e., manufacturer M_1 moves as the leader, manufacturer M_2 is the follower, and they move sequentially; (iii) $M_2 - M_1$ Stackelberg game, i.e., manufacturer M_1 moves as the leader, manufacturer M_2 is the follower, and they move sequentially.

The two manufacturers set price decisions with the goal of maximizing their own profits, and the retailer decides the corresponding retail prices of the two products after learning of the manufacturers' decision to maximize their profits. By backward induction, we first derive the retailer's response functions about the manufacturers' decision variables (p_0, w_1, w_2) in Proposition 1:

$$\begin{aligned}\prod_{R}(p_1, p_2) &= (p_1 - w_1)D_1 + (p_2 - w_2)D_2 - \frac{\mu\theta_1 s^2}{2(\theta_0 + \theta_1)} \\ &= (p_1 - w_1)(a_1 - k_1p_1 + \delta p_0 - \gamma_2p_2 + \theta_1 s) \\ &\quad + (p_2 - w_2)(a_2 - k_2p_2 - \gamma_1p_0 - \gamma_2p_1 + \theta_1 s) \\ &\quad - \frac{\mu\theta_1 s^2}{2(\theta_0 + \theta_1)}.\end{aligned} \tag{7}$$

Table 1: Notations and corresponding descriptions.

Notation	Description
c_i	Manufacturer M_i's unit cost of product i, $i = 1, 2$
w_i	Wholesale price at which manufacturer M_i distributes product i to the retailer $i = 1, 2$
p_i	Unit retail price at which the retailer sells product i to final customers by the traditional channel $i = 1, 2$
p_0	Unit retail price at which the manufacturer M_i sells product 1 to final customers by its online channel
s	Service level of product 1 in both the direct channel and the traditional retail channel
a_0	Primary market base of product 1 of the online sales channel
a_i	Primary market base of product i of the traditional retail channel $i = 1, 2$
k_1	Sensitivity of product 1 in both the direct channel and the traditional retail channel
k_2	Sensitivity of product 2 in the traditional retail channel
δ	Cross-price sensitivity coefficient of product 1 in both the direct channel and the traditional retail channel
γ_1	Complementarity level between product 1 in the direct channel and product 2 in the traditional retail channel
γ_2	Complementarity level between products 1 and 2 in the traditional retail channel
θ_0	Service sensitivity coefficient of the demand in the direct channel
θ_1	Service sensitivity coefficient of the demand in the traditional retail channel
μ	Service cost coefficient
D_0	Consumer demand for product 1 through the online sales channel
D_1	Consumer demand for product 1 through the traditional retail channel
D_2	Consumer demand for product 2 through the traditional retail channel
$\prod_{M_i}$ and $\prod_{M_i}$	Manufacturer M_i and retailer profits, respectively, $i = 1, 2$.

Proposition 1. *After manufacturer M_1 gives the wholesale price w_1 and the direct price p_0 of product 1 and manufacturer M_2 gives the wholesale price w_2 of product 2, the retailer's optimal price response functions are*

$$p_1(p_0, w_1, w_2) = \frac{\gamma_1\gamma_2 + \delta k_2}{2(k_1k_2 - \gamma_2^2)}p_0 + \frac{1}{2}w_1 + \frac{(k_2 - \gamma_2)\theta_1 s + a_1k_2 - a_2\gamma_2}{2(k_1k_2 - \gamma_2^2)}, \tag{8}$$

$$p_2(p_0, w_1, w_2) = \frac{-k_1\gamma_1 - \delta k_2}{2(k_1k_2 - \gamma_2^2)}p_0 + \frac{1}{2}w_2 + \frac{(k_1 - \gamma_2)\theta_1 s + a_2k_1 - a_1\gamma_2}{2(k_1k_2 - \gamma_2^2)}. \tag{9}$$

The proof of Proposition 1 and the other remaining proofs appear in Appendix A.

4.1. $M_1 - M_2$ Bertrand Game. Consider a Bertrand game model in which two manufacturers make price decisions simultaneously to maximize their own profits after finding out the retailer's response functions can be expressed as follows:

$$\begin{cases} \max\limits_{(p_0,w_1)} \prod\limits_{M_1}(p_0, w_1, p_1(p_0, w_1, w_2), p_2(p_0, w_1, w_2)), \\ \max\limits_{(w_2)} \prod\limits_{M_2}(w_2, p_1(p_0, w_1, w_2), p_2(p_0, w_1, w_2)). \end{cases} \tag{10}$$

Thus, the proposition of optimal price decisions for manufacturers can be obtained.

Proposition 2. *In the Bertrand game model, manufacturers M_1 and M_2 make decisions simultaneously, and the optimal wholesale price w_1^* and retail price p_1^* of manufacturer M_1 for product 1 and the optimal wholesale price w_2^* of manufacturer M_2 for product 2 are*

$$p_0^* = \frac{A_1}{A}, \quad w_1^* = \frac{A_2}{A}, \quad w_2^* = \frac{A_3}{A}, \tag{11}$$

where A, A_1, A_2, and A_3 are constants defined in Appendix B.

Substituting (11) into (8) and (9), the retailer's optimal equilibrium prices for product 1 and product 2 are obtained:

$$p_1^* = \frac{\gamma_1\gamma_2 + \delta k_2}{2(k_1k_2 - \gamma_2^2)}p_0^* + \frac{1}{2}w_1^* + \frac{(k_2 - \gamma_2)\theta_1 s + a_1k_2 - a_2\gamma_2}{2(k_1k_2 - \gamma_2^2)},$$
$$p_2^* = \frac{-k_1\gamma_1 - \delta k_2}{2(k_1k_2 - \gamma_2^2)}p_0^* + \frac{1}{2}w_2^* + \frac{(k_1 - \gamma_2)\theta_1 s + a_2k_1 - a_1\gamma_2}{2(k_1k_2 - \gamma_2^2)}. \tag{12}$$

4.2. $M_1 - M_2$ Stackelberg Game. The Stackelberg game will be implemented considering sequential decision-making by the two manufacturers. In the $M_1 - M_2$Stackelberg mode, manufacturer M_1 acts as the leader and initially announces wholesale price w_1 and direct price p_0 for product 1 first. Then, as the follower, manufacturer M_2 subsequently decides the wholesale price w_2 after knowing the decisions of manufacturer M_1. As the ultimate follower, the retailer will set the retail prices p_1 and p_2 of the two products to maximize his profit according to the manufacturers' decisions. The $M_1 - M_2$ Stackelberg game model can be formulated as

$$\begin{cases} \max\limits_{(p_0,w_1)} \prod\limits_{M_1} (p_0, w_1, p_1(p_0, w_1, w_2(p_0, w_1)), P_2(p_0, w_1, w_2(p_0, w_1))), \\ \max\limits_{(w_2)} \prod\limits_{M_2} (w_2, p_1(p_0, w_1, w_2), p_2(p_0, w_1, w_2)). \end{cases} \quad (13)$$

After observing the retailer's price response to (p_0, w_1, w_2) and given manufacturer M_1's pricing decisions, we derive manufacturer M_2's response function for (p_0, w_1) in Proposition 3.

Proposition 3. *After manufacturer M_1 gives the direct price p_0 and wholesale price w_1 for product 1, manufacturer M_2's response function can be obtained as*

$$w_2(p_0, w_1) = -\frac{\gamma_1}{2k_2} p_0 - \frac{\gamma_2}{2k_2} w_1 + \frac{a_2 + \theta_1 s}{2k_2} + \frac{c_2}{2}. \quad (14)$$

By backward induction, after observing the response functions of the retailer and manufacturer M_2, i.e., (8), (9), and (14), manufacturer M_1 will make price decisions to maximize his profit. Then, substituting manufacturer M_1's optimal price decisions into the response functions of the retailer and manufacturer M_2, we can obtain the optimal pricing strategies, which are shown in Proposition 4.

Proposition 4. *In the $M_1 - M_2$ Stackelberg structure, manufacturer M_1's direct price p_0^* and wholesale price w_1^* and manufacturer M_2's wholesale price w_2^* and the retailer's optimal retail price p_1^* and p_2^* are, respectively, given by*

$$p_0^* = \frac{B_1 a_0 + B_2 a_1 + B_3 a_2 + B_4 c_2 + B_5 s}{B} + \frac{1}{2} c_1, \quad (15)$$

$$w_1^* = \frac{B_6 a_0 + B_7 a_1 + B_8 a_2 + B_9 c_2 + B_{10} s}{B} + \frac{1}{2} c_1, \quad (16)$$

$$w_2^* = -\frac{\gamma_1}{2k_2} p_0^* - \frac{\gamma_2}{2k_2} w_1^* + \frac{a_2 + \theta_1 s}{2k_2} + \frac{c_2}{2}, \quad (17)$$

$$p_1^* = \frac{\gamma_1 \gamma_2 + \delta k_2}{2(k_1 k_2 - \gamma_2^2)} p_0^* + \frac{1}{2} w_1^* + \frac{(k_2 - \gamma_2)\theta_1 s + a_1 k_2 - a_2 \gamma_2}{2(k_1 k_2 - \gamma_2^2)}, \quad (18)$$

$$p_2^* = \frac{-k_1 \gamma_1 - \delta k_2}{2(k_1 k_2 - \gamma_2^2)} p_0^* + \frac{1}{2} w_2^* + \frac{(k_1 - \gamma_2)\theta_1 s + a_2 k_1 - a_1 \gamma_2}{2(k_1 k_2 - \gamma_2^2)}, \quad (19)$$

where B and B_i $(i = 1, \ldots, 10)$ are constants, as defined in Appendix B.

4.3. $M_2 - M_1$ Stackelberg Game. In the $M_2 - M_1$ Stackelberg model, manufacturer M_2 acts as the leader and initially announces wholesale price w_2 of product 2 first. As the follower, manufacturer M_1 subsequently decides direct price p_0 and wholesale price w_1 after finding out the decisions of manufacturer M_2. Similar to the previous case, the retailer, as the final follower, will set the retail prices p_1 and p_2 of the two products to maximize his profit according to the manufacturers' decisions. The $M_1 - M_2$ Stackelberg game model can be formulated as

$$\begin{cases} \max\limits_{(w_2)} \prod\limits_{M_2} (w_2, p_0(w_2), p_1(p_0(w_2), w_1(w_2), w_2), p_2(p_0(w_2), w_1(w_2), w_2)), \\ \max\limits_{(p_0,w_1)} \prod\limits_{M_1} (p_0, w_1, p_1(p_0, w_1, w_2), p_2(p_0, w_1, w_2)). \end{cases} \quad (20)$$

Given manufacturer M_2's pricing decision, we can derive manufacturer M_1's response function about w_2 after observing the retailer's price responses, which are shown in Proposition 5.

Proposition 5. *After manufacturer M_2 gives the wholesale price w_2 for product 2, manufacturer M_1's response function for w_2 can be obtained as*

$$p_0(w_2) = \frac{C_1 a_0 + C_2 a_1 + C_3 a_2 + C_4 w_2 + C_5 s}{C} + \frac{1}{2} c_1, \quad (21)$$

$$w_1(w_2) = \frac{C_6 a_0 + C_7 a_1 + C_8 a_2 + C_9 w_2 + C_{10} s}{C} + \frac{1}{2} c_1, \quad (22)$$

where C and C_i $(i = 1, \ldots, 10)$ are constants, as defined in Appendix B.

By backward induction, after observing the response functions of the retailer and manufacturer M_1, i.e., (8), (9), (21), and (22), manufacturer M_2 will make price decisions to maximize his profit. Then, by substituting manufacturer M_2's optimal price decisions into the response functions of the retailer and manufacturer M_1, we can obtain the optimal pricing strategies, which are shown in Proposition 6.

Proposition 6. *In the $M_2 - M_1$ Stackelberg structure, manufacturer M_2's wholesale price w_2^* is given by*

$$w_2^* = \frac{a_2 + \theta_1 s - \gamma_1 E_1 - \gamma_2 E_2}{2E} + \frac{1}{2} c_2, \quad (23)$$

where E, E_1, and $E_2$are constants defined in Appendix B.

Substituting (23) into (21) and (22), manufacturer M_1's optimal equilibrium prices p_0^* and M_1 for product 1 are obtained as follows:

$$p_0^* = \frac{C_1 a_0 + C_2 a_1 + C_3 a_2 + C_4 w_2^* + C_5 s}{C} + \frac{1}{2} c_1, \quad (24)$$

$$w_1^* = \frac{C_6 a_0 + C_7 a_1 + C_8 a_2 + C_9 w_1^* + C_{10} s}{C} + \frac{1}{2} c_1. \quad (25)$$

Subsequently, the retailer's optimal retail prices for the two products can be obtained by substituting (24) and (25) back into (8) and (9):

$$p_1^* = \frac{\gamma_1 \gamma_2 + \delta k_2}{2\left(k_1 k_2 - \gamma_2^2\right)} p_0^* + \frac{1}{2} w_1^* + \frac{(k_2 - \gamma_2)\theta_1 s + a_1 k_2 - a_2 \gamma_2}{2\left(k_1 k_2 - \gamma_2^2\right)}, \quad (26)$$

$$p_2^* = \frac{-k_1 \gamma_1 - \delta k_2}{2\left(k_1 k_2 - \gamma_2^2\right)} p_0^* + \frac{1}{2} w_2^* + \frac{(k_1 - \gamma_2)\theta_1 s + a_2 k_1 - a_1 \gamma_2}{2\left(k_1 k_2 - \gamma_2^2\right)}. \quad (27)$$

5. Sensitivity Analysis

In this section, the feasibility of the problem model involved in this paper is verified through numerical examples. We also show the sensitivity analysis of key parameters and derive some managerial implications from it. Based on the problem background and corresponding assumptions, the required parameters are given in Table 2.

The optimal pricing under three kinds of game models can be obtained by substituting the parameter values into the models and solving them, as shown in Table 3; the profits of the members and of the whole supply chain are shown in Table 4.

From Table 3, we can observe the following:

(1) In the case of the $M_1 - M_2$ Stackelberg where manufacturer M_1 acts as the leader, the optimal pricing for product 1 (p_0^*, w_1^*, p_1^*) achieves maximum values, while the optimal pricing for product 2 (w_2^*, p_2^*) achieves minimum values. However, in the case of the $M_2 - M_1$ Stackelberg where manufacturer M_2acts as the leader, the result is the opposite.

(2) The optimal pricing in the case of the $M_1 - M_2$ Bertrand is always between the other two scenarios because the two manufacturers have equal status in this situation, and no single manufacturer can hold a significant pricing advantage.

(3) In all cases, the inequality relation $w_1^* < p_0^* < p_1^*$ exists, which is reasonable, and $w_1^* < p_0^*$ guarantees the existence of manufacturer M_1's offline channel. Otherwise, the retailer will not wholesale product 1 from manufacturer M_1 but will switch to manufacturer M_1's direct sales channel. Since manufacturer M_1 has a greater cost advantage than the retailer ($c_1 < w_1^*$), to obtain the competitive advantage of the direct sales channel, manufacturer M_1's direct price p_0^* can be lower than the retailer's optimal price p_1^* for product 1. Meanwhile, the retailer's offline retail channel has a better user experience and lower operation cost than manufacturer M_1's direct sales channel, which does not make the retailer's optimal pricing p_1^* for product 1 too low, so $p_0^* < p_1^*$ is reasonable.

Table 2: Value of parameters.

Parameter	Value	Parameter	Value
(a_0, a_1, a_2)	$(650, 600, 1000)$	(θ_0, θ_1)	$(0.4, 0.6)$
(k_1, k_2, δ)	$(4, 6, 0.8)$	(μ, s)	$(5, 5)$
(γ_1, γ_2)	$(0.2, 0.6)$	(c_1, c_2)	$(80, 20)$

Table 3: Optimal pricing decision under different scenarios.

Parameter	$M_1 - M_2$ Bertrand	$M_1 - M_2$Stackelberg	$M_2 - M_1$ Stackelberg
p_0	135.83	**135.90**	135.82
w_1	128.17	**128.44**	128.15
w_2	84.91	84.90	**85.19**
p_1	142.02	**142.16**	142.00
p_2	115.98	115.97	**116.12**

Table 4: Maximum profits of every firm and the total system under different scenarios.

	$M_1 - M_2$ Bertrand	$M_1 - M_2$ Stackelberg	$M_2 - M_1$ Stackelberg
$\prod_{M_1}$	14655	**14656**	14650
$\prod_{M_2}$	12640	12635	**12641**
$\prod_R$	**7037.6**	7021.1	6984.4
$\prod_{SC}$	**34333.6**	34312.1	34275.4

The above analyses are the static comparison and descriptive analyses of the optimal pricing strategy and profit when a certain service level and other key parameters are given. In order to investigate the impact of key parameters on the optimal strategy more deeply, dynamically and intuitively, we perform a sensitivity analysis on key parameters in the following sections. It is worth noting that the main objective of this paper is to study the impact of parameters such as the service level and product complementarity level (excluding the price elasticity coefficient) on the product pricing strategy and member profits. For the sake of simplicity, the impact of price elasticity coefficients (including the self-price elasticity coefficient and cross-price elasticity coefficient) on prices and profits is not elaborated here. The impact relationship is summarized in Table 5 (the influence trends of parameters k_1, k_2, and δ on the optimal prices and profits are analogous in different situations).

Table 5 summarizes the sensitivity analysis of the optimal prices and profits for the self-price elasticity coefficients ($k_1 k_2$) and the cross-price elasticity coefficient of the product 1 (δ) in different game models. From Table 5, we can clearly see the influence trends of parameters k_1, k_2, and δ on the prices and profits and will not elaborate on it in more detail. Next, our work focuses on the sensitivity analysis of the four

Table 5: Sensitivity analysis of optimal price and profit under different scenarios.

Parameter	p_0^*	w_1^*	w_2^*	p_1^*	p_2^*	$\prod_{M_1}^*$	$\prod_{M_2}^*$	$\prod_R^*$
k_1	↓	↓	↑	↓	↑	↓	↑	↓then↑
k_2	↑	↑	↓	↑	↓	↑	↓	↓
δ	↑	↑	↓	↑	↓	↑	↓	↑

types of parameters: the service level (s), product complementarity level (γ_1, γ_2), service sensitivity coefficient (θ_1, θ_2), and service cost coefficient (μ). The specific content and corresponding explanations are as follows.

5.1. Service Level s. Exploring the impact of the service level on the optimal strategy and the service cooperation strategy between manufacturer M_1 and the retailer is a major research objective of this paper. In Section 4, we have obtained the analytical solutions of the optimal pricing strategy in each case, and we can derive the expressions of the optimal profit function of each member, all of which can be expressed as the relationship with service level s. Therefore, to further analyse the impact of service level s on optimal pricing strategy and profits, we fixed the values of other key parameters and changed only the service level s within a certain range. The results are shown in Figures 2 and 3.

From Figure 2, we can obtain the following results:

(1) Figures 2(a)–2(d) show that all optimal pricing ($p_0^*, p_1^*, p_2^*, w_1^*, w_2^*$) in the dual-channel supply chain are affected by the service level s and increase with the increase in service level s because as the service level increases, more service costs are paid, and the retailer and manufacturer M_1 must compensate for the increased costs by increasing the price of product 1 to obtain more profits. Product 2 is the complementary product of product 1, and customers can achieve the required utility only by purchasing two products at the same time. Therefore, the process of increasing the price of product 1 with the increase in the service level will also drive the price increase for product 2.

(2) Comparing the left and right sides of Figure 2, we can find that when manufacturer M_1 (M_2) dominates, its optimal pricing will be higher than in other pricing decision models because the dominant party in the supply chain has the pricing advantage of the highest profit.

Figure 3 shows that when the values of other parameters are fixed and the service level s varies within a certain range, the optimal profits of the retailer, manufacturer M_1, and manufacturer M_1 change in different decision models.

From Figures 3(a)–3(d), the following results can be obtained:

(1) Figure 3(a) shows that, as the service level s increases within a certain range, the retailer's optimal profit function has a similar trend in three different game models, i.e., with the increase in s, the function increases first and then decreases because the increase in retailers' service level will lead to an increase in demand, the resulting profit growth is greater than the additional cost incurred to improve service levels, and total profit increases. However, when the service level reaches a certain threshold, the magnitude of the relationship between the two is reversed, and the total profit begins to decline. It can be seen that, for retailers, a higher service level s is not always better. A higher service level can bring more demand and profits, but the corresponding costs will be even greater. In addition, we can see that the retailer's profit in the $M_1 - M_2$ Bertrand model is greater than that in the $M_1 - M_2$ Stackelberg model when the values of the parameters involved are given, while the profit obtained in the $M_2 - M_1$ Stackelberg model is lowest.

(2) Figure 3(b) shows that when the service level s is low, the optimal profit function in the different game models of manufacturer M_1 increases as the service level increases. As we continue to improve the service level, we will find that there is still a threshold after which manufacturer M_1's profit function begins to decline, as shown in Figure 3(c). In other words, the trend in which manufacturer M_1's profit function changes with the service level s is similar to that of the retailer; that is, it first rises and then falls. However, it is apparent that the threshold at which manufacturer M_1's profit function begins to fall is greater than the threshold at which the retailer's profit function begins to decline because when manufacturer M_1 supplies product 1 to the retailer, the relevant service of product 1 in the direct channel is entrusted to the retailer in the form of service cost sharing. Then, the increase in the service level will increase manufacturer M_1's demand for both online and offline channels. Although manufacturer M_1 will share part of the service cost in the process, the cost of this part is less than the profit growth caused by the increase in demand, and the magnitude of the relationship between the two will reverse only when the service level is particularly high (beyond the threshold). In addition, for manufacturer M_1, although the results of the different game models are not significantly different, the $M_1 - M_2$ Stackelberg model still demonstrates the highest profit. This finding is different from the research of Zhao and Hou et al. (2017), who stated that manufacturer M_1 is not the most profitable in the $M_1 - M_2$ Stackelberg game model because higher price increases and the provision of service by the retailer lead to a reduction in demand for manufacturers over profit. However, in our research, as the retailer accepts the commission of manufacturer M_1 and provides services to both the direct channel and the offline channel, the reduced demand of manufacturer M_1 is compensated to ensure that its profit is the highest in the $M_1 - M_2$ Stackelberg game model. This finding is

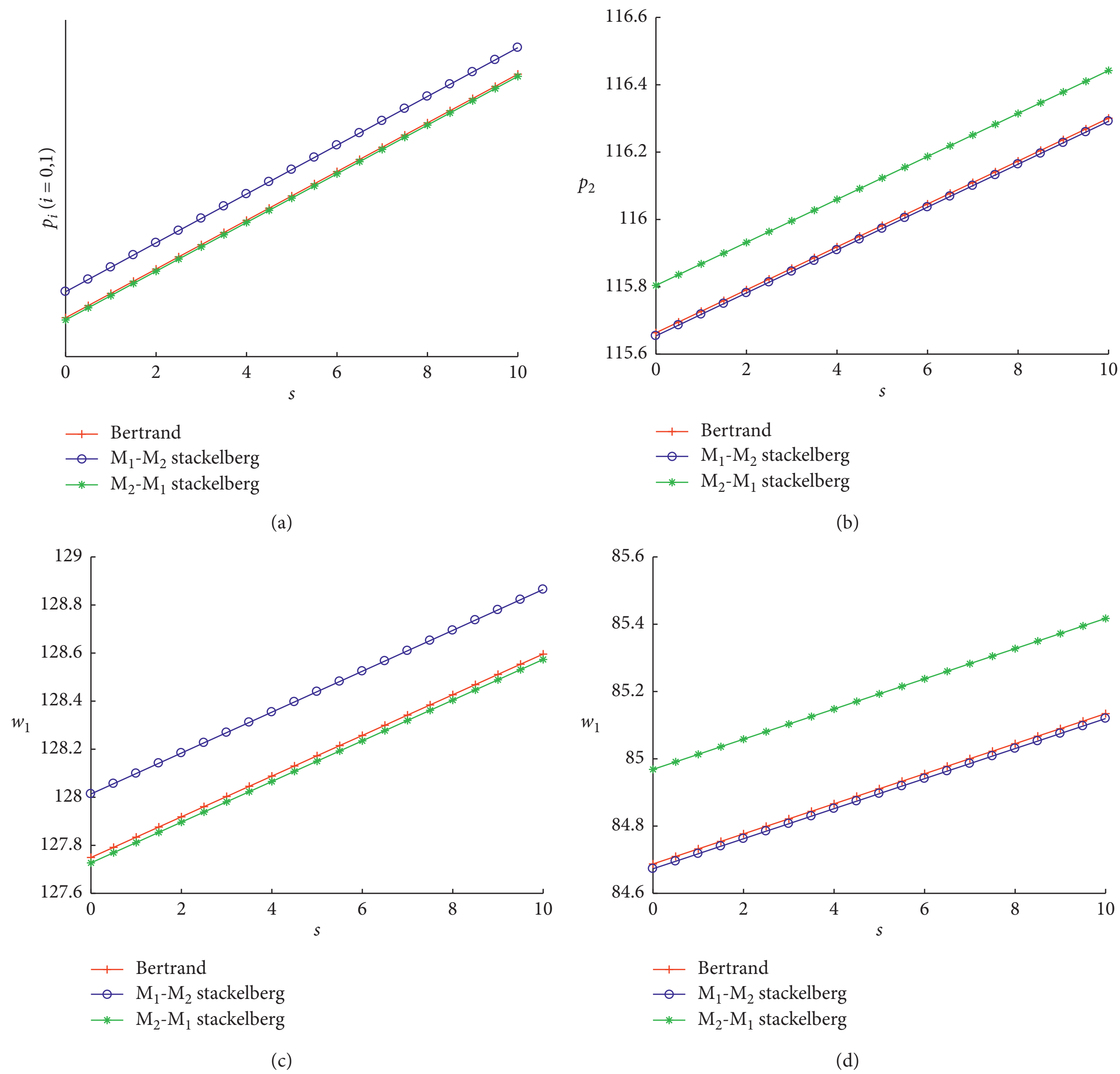

Figure 2: Influence of s on price functions under different scenarios.

consistent with manufacturer M_1's goal of maximizing its own profit level as a game leader.

(3) Figure 3(d) shows that manufacturer M_2's optimal profit function increases with the increase in the service level s in the three different game models because product 1 and product 2 are complementary products, and providing a high level service for product 1 can increase its demand while also causing an increase in demand for product 2 so that the profit function of manufacturer M_2 continues to rise. In other words, manufacturer M_2 plays a free-riding role in the process of service cooperation between manufacturer M_1 and the retailer for product 1 and enjoys the profit growth brought by the service cooperation between the two parties without apportioning the service cost.

Summarizing the results of Figures 2 and 3, we can obtain the following management insight:

Insight 1

(i) An increase in the service level will increase the service cost, which will lead to an increase in the optimal pricing of policy makers.

(ii) Increasing the service level can increase the profitability of the retailer and manufacturer M_1, but a higher service level is not always better because an excessive service level can lead to a high service cost, which in turn leads to a decline in profits.

(iii) The service level threshold that causes manufacturer M_1 to begin to lose profits is significantly greater than that for the retailer, which shows that

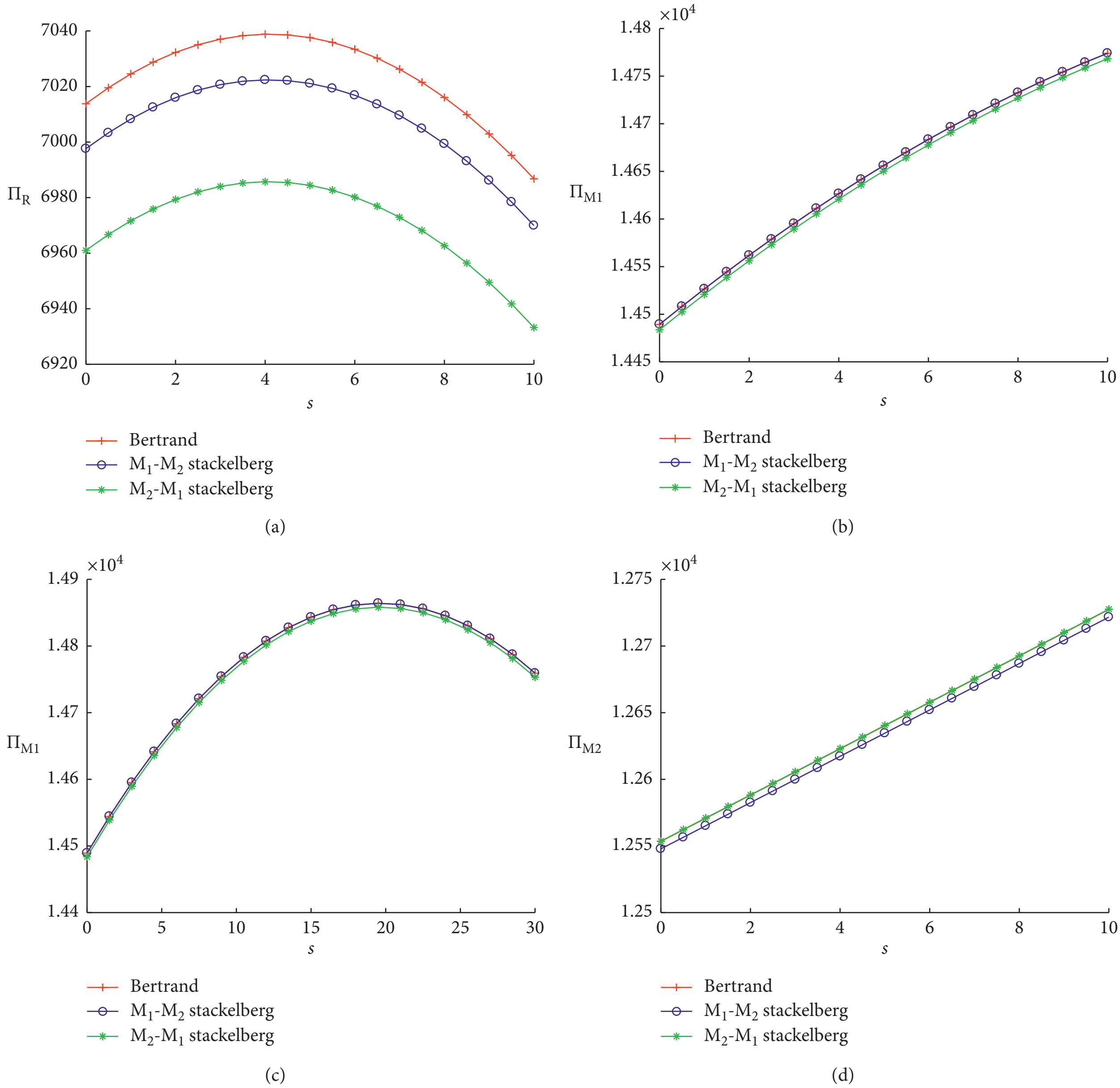

Figure 3: Influence of s on profit functions under different scenarios.

service level s has more room for improvement in the profit growth of manufacturer M_1 than that of the retailer. Therefore, manufacturer M_1 should increase the proportion of service cost sharing to ensure that retailer can improve the service level as much as possible without impairing its profits and ultimately achieving more profit growth.

5.2. Complementarity Level. In this section, we examine the impact of the level of complementarity between product 1 and product 2 in different channels on the optimal pricing strategies and profit functions. The complementarity levels of products in this paper includes the complementarity level between product 1 in the direct marketing channel and product 2 in the retail channel γ_1, as well as the complementarity level between product 1 in the retail channel and product 2 in the retail channel γ_2. It is worth noting that, for the optimal pricing and profit functions of the three different decision models, when the product complementarity level varies within a certain range, the functions' trends are similar. Therefore, it is not necessary to present the results of the analysis for all models. Here, we take the Bertrand game decision model as an example to introduce the impact of changes in product complementarity on optimal pricing and profit.

Figures 4(a) and 4(b) show the change in optimal pricing and profit functions when the complementarity level is between product 1 in the direct channel and product 2 in the retail channel changes. At the same time, Figures 4(c) and 4(d) show the change in optimal pricing and profit functions

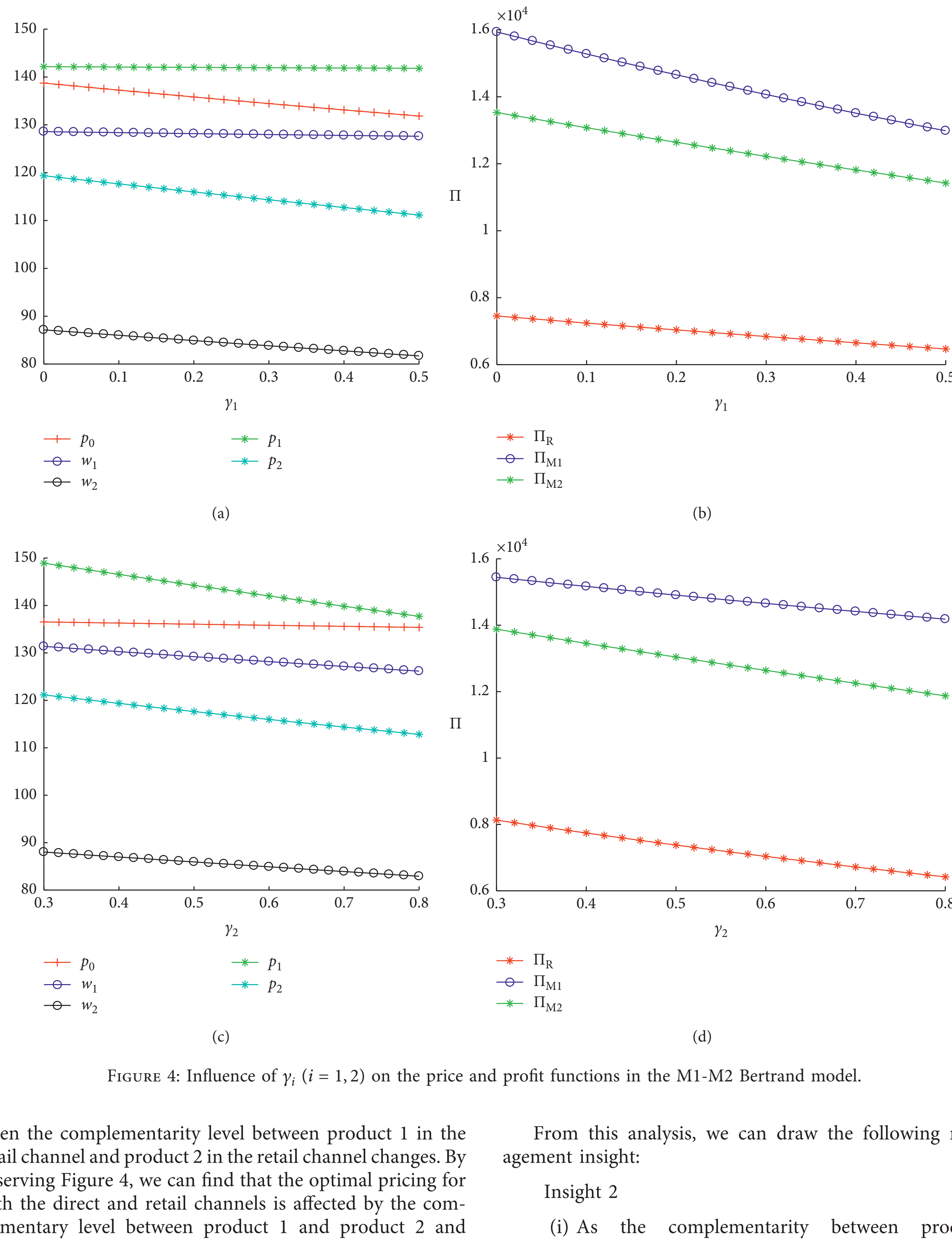

Figure 4: Influence of γ_i $(i = 1, 2)$ on the price and profit functions in the M1-M2 Bertrand model.

when the complementarity level between product 1 in the retail channel and product 2 in the retail channel changes. By observing Figure 4, we can find that the optimal pricing for both the direct and retail channels is affected by the complementary level between product 1 and product 2 and shows a negative correlation. Meanwhile, with the increase in the complementarity level, the optimal profits of the retailer, manufacturerM_1, and manufacturerM_2 significantly decrease.

From this analysis, we can draw the following management insight:

Insight 2

(i) As the complementarity between products strengthens, the optimal pricing decreases, which will further reduce the profit. The main reason for this phenomenon is that as the product complementarity increases, customers become less selective when purchasing products, which will reduce customers' desire to purchase.

(ii) Merchants should lower product pricing and attract customers to buy at the expense of profit. An alternative for such merchants is to reduce the complementarity between the two products to improve the optimal pricing of products, but products with low complementarity are easily imitated or replaced and have no competitive advantage.

5.3. Service Sensitivity Coefficients. The service sensitivity coefficient reflects the degree of customers' response to channel services, which is reflected in the impact of service level changes in customer demand. In this paper, the retailer provides the same level of related services to product 1 in the direct channel and the retail channel, but the customer's service sensitivity coefficients for different channels are not necessarily the same. Here, we change the service sensitivity coefficients of the two channels within a certain range, and the profit changes for channel members in different decision models are shown in Figure 5.

The following results can be observed from Figure 5:

(1) Figure 5(a) shows how the retailer's optimal profit function varies with the service sensitivity coefficients in different decision models. In the three different game models, the retailer's profit function has a similar trend as the service sensitivity coefficient of the two channels; that is, it increases with the increase in the service sensitivity coefficient. Additionally, the increment speed of a retailer's profit function with the service sensitivity coefficient of the retail channel is faster than that of the direct channel. At the same time, we can also see that the retailer's profit in the $M_1 - M_2$ Bertrand model is higher than that in the $M_1 - M_2$ Stackelberg model, while the profit in the $M_2 - M_1$ Stackelberg model is the smallest, which is consistent with the results of the previous numerical analysis.

(2) Figure 5(b) shows how manufacturerM_1's optimal profit function varies with the service sensitivity coefficients in different decision models. Similar to the change in the retailer's profit function, manufacturerM_1's profit function also shows an increasing trend with the increase in service sensitivity coefficients in the three different game models. However, unlike the retailer's profit function, manufacturerM_1's profit function increases more quickly with the service sensitivity coefficient of the direct marketing channel than that of the retail channel. In addition, in the process of the change in service sensitivity coefficients in the two channels, manufacturerM_1's profit in the $M_1 - M_2$ Stackelberg model is always greater than that in the $M_1 - M_2$ Bertrand model, and the profit in the $M_2 - M_1$ Stackelberg model is the lowest. However, the profit of manufacturer M_1 in the $M_1 - M_2$ Stackelberg model is very similar to that of the $M_1 - M_2$Bertrand model, so the profit function surface graph corresponding to the $M_1 - M_2$ Bertrand model in Figure 5(b) is not easy to observe.

(3) Figure 5(c) shows the variation in manufacturerM_2's profit function with the service sensitivity coefficients in three game models. Unlike the trend in changes in profit functions of retailer and manufacturer M_1, the profit function of manufacturer M_2 increases significantly as the service sensitivity coefficient of the retail channel increases, but it declines slightly as the service sensitivity coefficient of the direct channel increases. In addition, the relationship between the size of the profit function of manufacturerM_2 and manufacturerM_1 is the opposite in the three decision models. That is to say, the profit of manufacturerM_2 in the $M_2 - M_1$ Stackelberg model is greater than that of the $M_1 - M_2$ Bertrand model, and the profit in the $M_1 - M_2$Stackelberg model is the lowest. At the same time, the profits of the manufacturer in the Stackelberg model are similar to those of the Bertrand model. Moreover, the profits of manufacturer M_2 in the $M_2 - M_1$ Stackelberg model are similar to that of the $M_1 - M_2$ Bertrand model, so it is not easy for us to observe the profit function surface figure corresponding to the $M_1 - M_2$ Bertrand model in Figure 5(c).

Based on the above results, we can obtain the following management insight:

Insight 3

(i) For the retailer and manufacturer M_1, it is possible to enhance customers' service sensitivity coefficient for the channel by developing different marketing or service strategies to achieve profit growth.

(ii) For manufacturer M_2, since product 2 is sold only through the retail channel, the increase in the service sensitivity coefficient in the retail channel can improve the firm's profit level. Therefore, manufacturer M_2, which refuses to share the service cost, should not exist only as a free rider. Instead, it should be a participant in the retail channel and works with the retailer to improve the customer service sensitivity of the retail channel as much as possible.

5.4. Service Cost Coefficient. The service cost coefficient is used to reflect the impact of the service level on the service cost when the service level changes, which will directly affect the service cost. In our research, the retailer is responsible for providing related services and generating corresponding service costs. Manufacturer M_1 cooperates with the retailer in service and shares part of the service cost, but manufacturer M_2 is not involved in the process. Therefore, the service cost coefficient μ will affect the profit functions of the retailer and manufacturer M_1, and manufacturer M_2's profit function is independent of it. In addition, it is worth noting

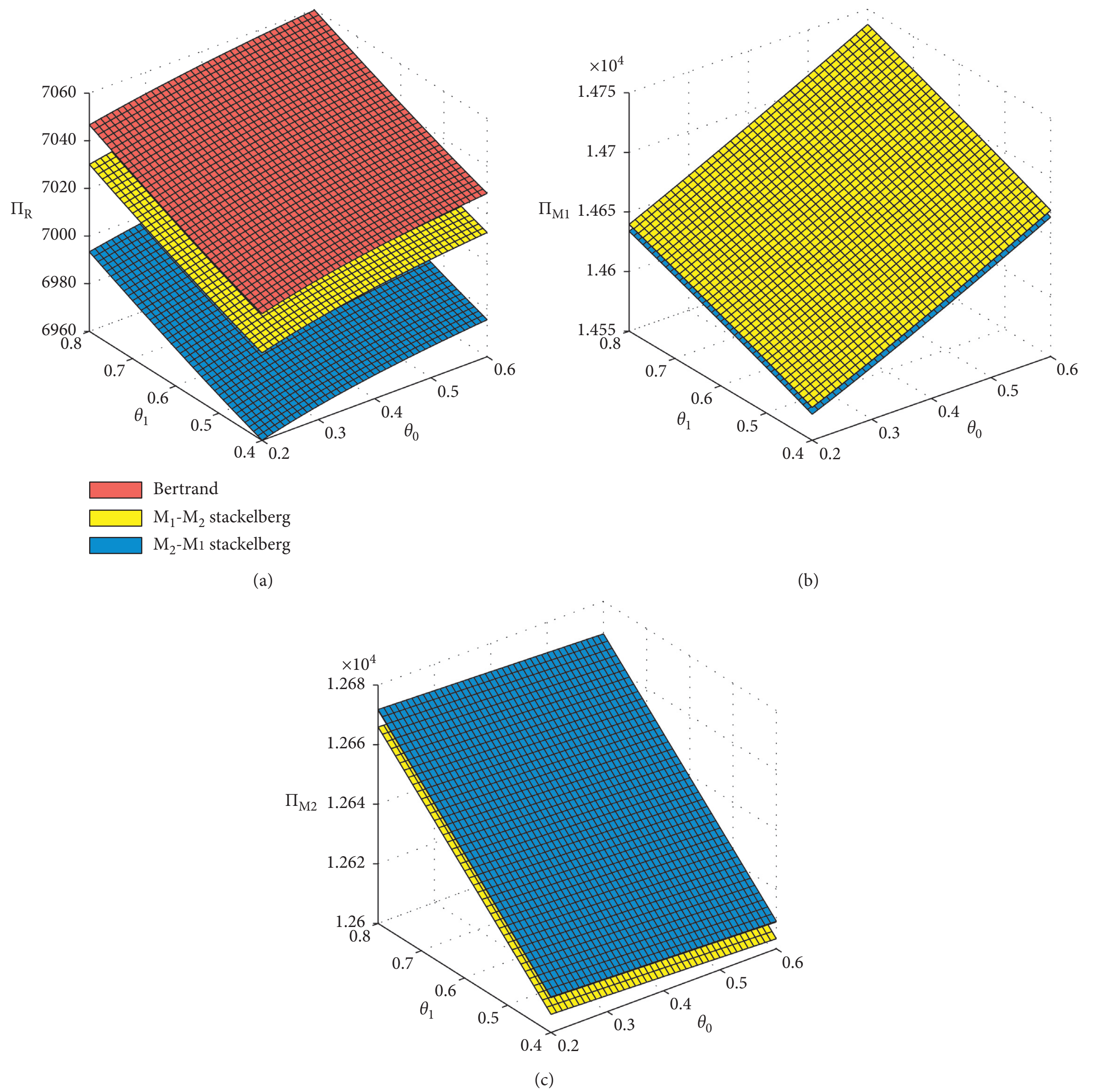

Figure 5: Influence of θ_i $(i = 1, 2)$ on profit functions under different scenarios.

that the optimal pricing strategy of supply chain members is also unaffected by the service cost coefficient. Therefore, in this part, we need to analyse only how the profit functions of the retailer and manufacturer M_1 change with the service cost coefficient, as shown in Figure 6.

Figures 6(a) and 6(b) show the change in the profit function of the retailer and manufacturer M_1, respectively, when the service cost coefficient μ is within a certain range. It can be seen that, with the increase in the service cost coefficient μ, both the retailer's and manufacturer M_1's profit functions show a downward trend. The reason for this result is obvious: when the service level is fixed, the service cost will increase with an increase in the service cost coefficient, which will cause profit to decline.

The service cost coefficient reflects the retailer's comprehensive level or technical ability to provide services and is directly related to its service cost expenditure. As the retailer's comprehensive level or technical capability to provide services increases, the service cost coefficient lowers, and less service cost will be generated at a certain service level. In other words, when the service level is the same, as the service cost coefficient decreases, the service cost expenditure decreases. Therefore, we can obtain the following management insight:

Insight 4

(i) As a service provider, the retailer should take into account all factors and improve the service

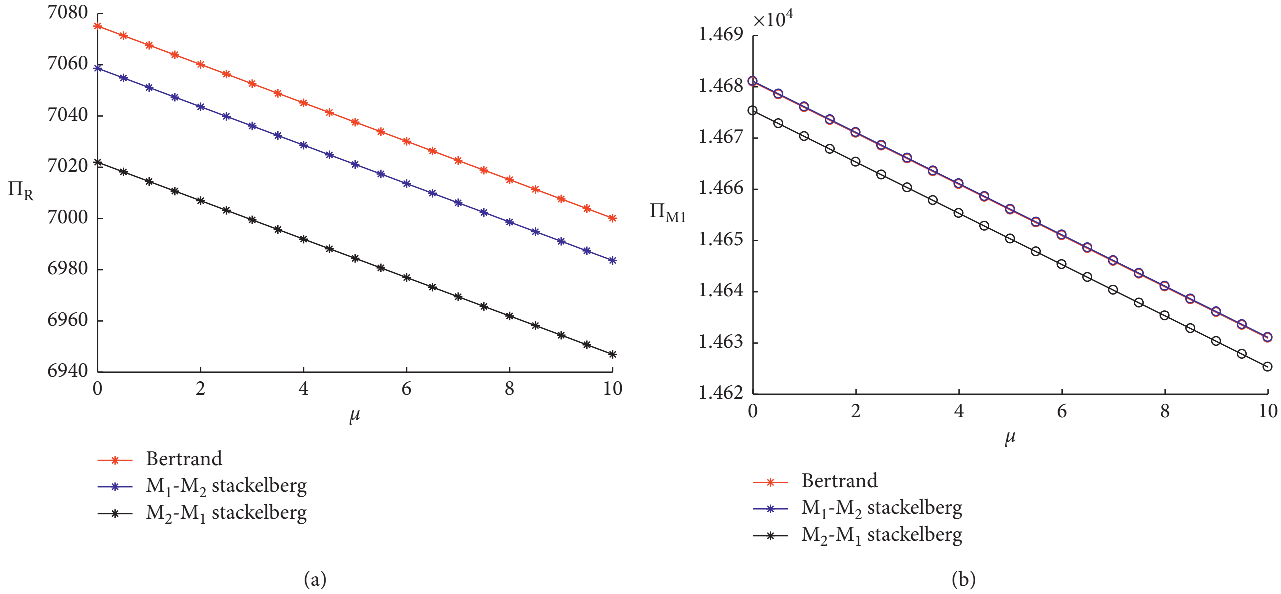

Figure 6: Influence of μ on profit functions under different scenarios.

operation mode to reduce the service cost coefficient and gain more profits.

(ii) Since manufacturer M_1 cooperates with the retailer in service and shares the service cost proportionally, the two firms should work together to reduce the service cost coefficient and achieve a win-win situation in which costs for both firms are reduced simultaneously.

6. Conclusions

In this paper, we study optimal pricing and service cooperation strategies for complementary products in a dual-channel supply chain system consisting of two manufacturers and one retailer. One of the two manufacturers provides product 1 to the retailer through the retail channel and sells product 1 to the consumer through a direct sales channel; that is, it competes with the retailer in the end customer market. Another manufacturer sells only complementary product 2 through the same retailer. In addition, the retailer provides services for product 1 and cooperates with the manufacturer of product 1 to share the resulting service cost. According to the different power structures of the two manufacturers and the retailer, we establish three pricing game models and obtain the corresponding equilibrium analytical solutions, and the strategies of service cooperation between the manufacturer of product 1 and the retailer are given. Numerical comparisons are made between the optimal pricing strategies and profit situations in three different game scenarios under given key parameters. Subsequently, the sensitivity analysis of each key parameter is carried out, and some valuable management insights are obtained.

The main findings of this paper are as follows: (i) when two manufacturers are on equal footing, the retailer has the advantage of obtaining the most profit. Otherwise, the leading manufacturer in the supply chain has the pricing advantage of maximizing profits. (ii) The increase in the service level within a certain range can bring about an increase in the profit of the service cost sharer. However, as the service level increases, the service cost and price will increase, which will lead to a decline in profits, so the service level cannot increase indefinitely. (iii) The product complementarity level is inversely proportional to the product's optimal pricing and member profit. Enterprises can reduce the level of complementarity between products to increase profits, or at the expense of profit, it can reduce product complementarity to enhance its competitive advantage. (iv) The profit function of supply chain members is positively related to the service sensitivity coefficient of the channel in which their products are located. By developing different marketing or service strategies to improve the sensitivity coefficient of customers to channel services, the profit of supply chain members can increase. (v) The service cost coefficient is significantly positively correlated with the service cost expenditure, and the impact on the service cost is a sustainable long term. The service cost sharer should optimize the service link by designing and implementing appropriate strategies to reduce unnecessary capital investment, thereby reducing the service cost coefficient and achieving the goal of reducing the service cost.

Our main aim is to study the impact of the channel's service level, service sensitivity coefficient, and complementarity level on the pricing strategies and maximum profits of two complementary products in a dual-channel supply chain under different market rights structures. This paper assumes that demand is a linear function of price and the service level and that both the manufacturer and the retailer engaged in service cooperation have symmetrical service cost information. However, in reality, demand is often subject to uncertainty due to many factors, and manufacturers are unlikely to know the exact information on retailer service costs in most cases. Therefore, future research can extend the model to include nonlinear demand functions and stochastic demand functions and can be extended to the case of asymmetric service cost information. Considering the consumption dependence of complementary products, future research can also be extended to the bundling and pricing strategies of complementary products. In addition, this paper studies a single complementary relationship. However, there are multiple complementary relations in practice; that is, products that can satisfy complementarity with a certain product are not unique. Then, the pricing problem of complementary and competitive products that coexist can provide an expansion direction for future research.

Appendix

A. All Proofs

Proof of Proposition 1. Given the wholesale prices w_1 and w_2 of the two manufacturers and the direct selling price p_0 of product 1, the Hessian matrix of the retail prices p_1 and p_2 is obtained by the retailer's profit function $\prod_R(p_1, p_2)$ as follows:

$$H_1 = \begin{bmatrix} -2k_1 & -2\gamma_2 \\ -2\gamma_2 & -2k_2 \end{bmatrix}. \tag{A.1}$$

According to the solution result of the Hessian matrix and the hypothesis that $k_i > \gamma_i$ $(i = 1, 2))$, $-2k_1 < 0$ and $4(k_1k_2 - \gamma_2^2) > 0$ are established, so $\prod_R(p_1, p_2)$ is jointly concave in p_1 and p_2. Therefore, for a given w_1 and w_2 and p_0, the optimal pricing of the retailer can be determined by its first-order partial derivatives $(\partial\prod_R(p_1, p_2, s)/\partial p_1) = 0$ and $(\partial\prod_R(p_1, p_2, s)/\partial p_2) = 0$. Thus, Proposition 1 is proven.

Proof of Proposition 2. We substitute (1), (2), (8), and (9) into (4) and calculate the Hessian matrix of manufacturer M_1's profit function $\prod_{M_1}(p_0, w_1)$ with respect to p_0 and w_1 as follows:

$$H_2 = \begin{bmatrix} \dfrac{\gamma_1^2 k_1 + \delta^2 k_2 + 2\delta\gamma_1\gamma_2}{k_1k_2 - \gamma_2^2} - 2k_1 & \delta \\ \delta & -k_1 \end{bmatrix}. \tag{A.2}$$

According to the parameter assumptions $2k_1^3k_2 - 2k_1^2\gamma_2^2 - \gamma_1^2k_1^2 - 2\delta^2k_1k_2 - 2\delta\gamma_1\gamma_2k_1 + \delta^2\gamma_2^2 > 0$ and $k_i > \delta, \gamma_i$ $(i = 1, 2)$, the Hessian matrix H_2 is negative definite. Therefore, $\prod_{M_1}(p_0, w_1)$ is jointly concave in p_0 and w_1.

By further substituting (3), (8), and (9) into (5) and calculating the first-order and second-order derivatives of manufacturer M_2's profit function $\prod_{M_2}(w_2)$ with respect to w_2, the following results are obtained:

$$\frac{d\prod_{M_2}(w_2)}{\mathrm{d}w_2} = \frac{1}{2}\left(a_2 + k_2c_2 - \gamma_1 p_0 - \gamma_2 w_1 + \theta_1 s\right) - k_2 w_2,$$
$$\frac{d^2\prod_{M_2}(w_2)}{\mathrm{d}w_2^2} = -k_2 < 0. \tag{A.3}$$

Thus, it can be seen that the profit function $\prod_{M_2}(w_2)$ is concave in w_2. Therefore, the optimal pricing of manufacturer M_1 and manufacturer M_2 can be determined by their first-order partial derivatives $(\partial\prod_{M_1}(p_0, w_1)/\partial p_0) = 0$, $(\partial\prod_{M_1}(p_0, w_1)/\partial w_1) = 0$, and $(d\prod_{M_2}(w_2)/dw_2) = 0$. Thus, Proposition 2 is proven.

Proof of Proposition 3. The proof of Proposition 2 shows that the profit function $\prod_{M_2}(w_2)$ is concave in w_2 after the retailer's optimal response functions are returned. Consequently, by setting $(d\prod_{M_2}(w_2)/\mathrm{d}w_2) = (1/2)(a_2 + k_2c_2 - \gamma_1 p_0 - \gamma_2 w_1 + \theta_1 s) - k_2 w_2 = 0$ and solving it, manufacturer M_2's optimal response function, i.e., (14), can be obtained, and Proposition 3 is proven.

Proof of Proposition 4. After observing the optimal response functions of the retailer and manufacturer M_2, i.e., (8), (9), and (14), manufacturer M_1 will set a pricing strategy with the goal of maximizing its profit. We substitute (1), (2), (8), (9), and (14) into manufacturer M_1's profit function, i.e., (4), and calculate the Hessian matrix with respect to p_0 and w_1 as follows:

$$H_3 = \begin{bmatrix} \dfrac{k_1\gamma_1^2 + \delta^2 k_2 + 2\delta\gamma_1\gamma_2}{k_1k_2 - \gamma_2^2} + \dfrac{\gamma_1^2}{2k_2} - 2k_1 & \delta + \dfrac{\gamma_1\gamma_2}{2k_2} \\ \delta + \dfrac{\gamma_1\gamma_2}{2k_2} & \dfrac{\gamma_2^2}{2k_2} - k_1 \end{bmatrix}. \tag{A.4}$$

According to the parameter assumptions $k_1k_2(4k_1^2k_2 - 6k_1\gamma_2^2 - 6\delta\gamma_1\gamma_2 - 3k_1\gamma_1^2 - 4\delta^2k_2) + \gamma_2^2(3\delta^2k_2 + 2k_1\gamma_1^2 + 4\delta\gamma_1\gamma_2 + 2k_1\gamma_2^2) > 0$ and $k_i > \delta, \gamma_i$ $(i = 1, 2)$, the Hessian matrix H_3 is negative definite. Therefore, $\prod_{M_1}(p_0, w_1)$is jointly concave in p_0 and w_1. By setting $(\partial\prod_{M_1}(p_0, w_1)/\partial p_0) = 0$ and $(\partial\prod_{M_1}(p_0, w_1)/\partial w_1) = 0$, (15) and (16) can be obtained. Upon further substituting (15) and (16) into (14), the authors can obtain (18), and by returning (15), (16), and (17) to (8) and (9), (18) and (19) can be obtained. Thus, Proposition 4 is proven.

Proof of Proposition 5. The proof of Proposition 2 shows that the profit function $\prod_{M_1}(p_0, w_1)$ is jointly concave in $p_0$and w_1 after the retailer's optimal response functions are returned. Therefore, for a given w_2, by setting

$(\partial\prod_{M_1}(p_0, w_1)/\partial p_0) = 0$ and $(\partial\prod_{M_1}(p_0, w_1)/\partial w_1) = 0$, (21) and (22) can be obtained. Thus, Proposition 5 is proven.

Proof of Proposition 6. After observing the optimal response functions of the retailer and manufacturer M_1, i.e., (8), (9), (21), and (22), manufacturer M_2 will set the price strategy with the goal of maximizing its profit. We substitute (3), (8), (9), (21), and (22) into manufacturer M_2's profit function, i.e., (5), and calculate the second-order derivative with respect to w_2 as follows:

$$\begin{aligned}\frac{d^2\prod_{M_2}(w_2)}{\mathrm{d}w_2^2} &= -k_2 - \frac{\gamma_1 C_4 + \gamma_2 C_9}{C}\\ &= -\frac{1}{C}\left(k_2 C + \gamma_1 C_4 + \gamma_2 C_9\right).\end{aligned} \tag{A.5}$$

Here, C, C_4, and C_9 are constants defined in Appendix B.

It follows from parameter assumption (*i*) that $C < 0$. Simultaneously, based on parameter assumption (*ii*) and $k_i > \delta, \gamma_i$ $(i = 1, 2)$, the authors can obtain $k_2 C + \gamma_1 C_4 + \gamma_2 C_9 < 0$ ($k_2 C + \gamma_1 C_4 + \gamma_2 C_9$ can be regarded as the inverse of parameter assumption (*ii*)). Thus, $(d^2\prod_{M_2}(w_2)/dw_2^2) < 0$ is established; that is, the profit function $\prod_{M_2}(w_2)$ is concave in w_2. By setting $(d\prod_{M_2}(w_2)/\mathrm{d}w_2) = 0$, (23) can be obtained. Upon further substituting (23) into (21) and (22), the authors can obtain (24) and (25), and finally, by returning (23), (24), and (25) to (8) and (9), (26) and (27) can be obtained. Thus, Proposition 6 is proven.

B. Notation

$$A = \begin{vmatrix} 2\lambda_1 & 2\delta & -\gamma_1 \\ 2\delta & -2k_1 & -\gamma_2 \\ -\gamma_1 & -\gamma_2 & -2k_2 \end{vmatrix},$$

$$A_1 = \begin{vmatrix} -2a_0 + (\lambda_1 + \delta)c_1 - 2\lambda_2 s - 2\lambda_3 & 2\delta & -\gamma_1 \\ -a_1 + \delta c_1 - \theta_1 s & -2k_1 & -\gamma_2 \\ -a_2 - k_2 c_2 - \theta_1 s & -\gamma_2 & -2k_2 \end{vmatrix},$$

$$A_2 = \begin{vmatrix} 2\lambda_1 & -2a_0 + (\lambda_1 + \delta)c_1 - 2\lambda_2 s - 2\lambda_3 & -\gamma_1 \\ 2\delta & -a_1 + \delta c_1 - \theta_1 s & -\gamma_2 \\ -\gamma_1 & -a_2 - k_2 c_2 - \theta_1 s & -2k_2 \end{vmatrix},$$

$$A_3 = \begin{vmatrix} 2\lambda_1 & 2\delta & -2a_0 + (\lambda_1 + \delta)c_1 - 2\lambda_2 s - 2\lambda_3 \\ 2\delta & -2k_1 & -a_1 + \delta c_1 - \theta_1 s \\ -\gamma_1 & -\gamma_2 & -a_2 - k_2 c_2 - \theta_1 s \end{vmatrix},$$

$$\lambda_1 = \frac{\gamma_1^2 k_1 + \delta^2 k_2 + 2\delta\gamma_1\gamma_2}{k_1 k_2 - \gamma_2^2} - 2k_1,$$

$$\lambda_2 = \theta_0 + \frac{\gamma_1\gamma_2\theta_1 + \delta k_2\theta_1 - \gamma_1 k_1\theta_1 - \delta\gamma_2\theta_1}{2\left(k_1 k_2 - \gamma_2^2\right)},$$

$$\lambda_3 = \frac{(\gamma_1\gamma_2 + \delta k_2)a_1 - (\gamma_1 k_1 + \delta\gamma_2)a_2}{2\left(k_1 k_2 - \gamma_2^2\right)},$$

$$\begin{aligned} B &= 2\left[\gamma_2^2\left(2k_1\gamma_2^2 + 4\delta\gamma_1\gamma_2 + 3\delta^2 k_2 + 2k_1\gamma_1^2 - 6k_1^2 k_2\right)\right.\\ &\quad\left. + k_1 k_2\left(4k_1^2 k_2 - 4\delta^2 k_2 - 3k_1\gamma_1^2 - 6\delta\gamma_1\gamma_2\right)\right],\\ B_2 &= -\gamma_2^2\left(2\gamma_1\gamma_2 + 3\delta k_2\right) + k_1 k_2\left(4\delta k_2 + 3\gamma_1\gamma_2\right),\\ B_3 &= \left(k_1\gamma_1 + \delta\gamma_2\right)\left(2\gamma_2^2 - 3k_1 k_2\right),\\ B_4 &= \left(k_1 k_2\gamma_1 + \delta k_2\gamma_2\right)\left(\gamma_2^2 - k_1 k_2\right),\\ B_5 &= \gamma_2^2\left(2\gamma_2^2\theta_0 + 2\delta\gamma_2\theta_1 - 2\gamma_1\gamma_2\theta_1 - 3\delta k_2\theta_1\right.\\ &\quad\left. + 2k_1\gamma_1\theta_1 - 6k_1 k_2\theta_0\right)\\ &\quad + k_1 k_2\left(4k_1 k_2\theta_0 + 4\delta k_2\theta_1\right.\\ &\quad\left. - 3k_1\gamma_1\theta_1 - 3\delta\gamma_2\theta_1 + 4\gamma_1\gamma_2\theta_1\right),\\ B_6 &= 2\gamma_1\gamma_2\left(k_1 k_2 - \gamma_2^2\right) + 4\delta k_1 k_2^2,\\ B_7 &= \gamma_1\gamma_2\left(2\gamma_1\gamma_2 - \delta k_2\right) + k_1 k_2\left(4k_1 k_2 - 3\gamma_1^2 - 4\gamma_2^2\right),\\ B_8 &= 2\left(k_1\gamma_2 + \delta\gamma_1\right)\left(\gamma_2^2 - k_1 k_2\right) - \delta k_2\left(k_1\gamma_1 + \delta\gamma_2\right),\\ B_9 &= \left(\gamma_2^2 - k_1 k_2\right)\left(2k_1 k_2\gamma_2 + \delta k_2\gamma_1\right)\\ &\quad + k_2\gamma_2\left(2\delta\gamma_1\gamma_2 + \delta^2 k_2 + k_1\gamma_1^2\right),\\ B_{10} &= 2\left(\gamma_2^2 - k_1 k_2\right)\left(k_1\gamma_2\theta_1 - \gamma_1\gamma_2\theta_0 + \gamma_1^2\theta_1 + \delta\gamma_1\theta_1\right.\\ &\quad\left. - 2\delta k_2\theta_0 - 2k_1 k_2\theta_1\right) - k_2\left(\delta + \gamma_1\right)\left(k_1\gamma_1 + \delta\gamma_2\right)\theta_1,\\ C &= 2\left[\left(k_1\gamma_1 + \delta\gamma_2\right)^2 + 2\left(k_1 k_2 - \gamma_2^2\right)\left(\delta^2 - k_1^2\right)\right],\\ C_1 &= 2k_1\left(\gamma_2^2 - k_1 k_2\right),\\ C_2 &= \delta\gamma_2^2 - k_1\gamma_1\gamma_2 - 2\delta k_1 k_2,\\ C_3 &= k_1\left(k_1\gamma_1 + \delta\gamma_2\right),\\ C_4 &= \left(k_1 k_2 - \gamma_2^2\right)\left(k_1\gamma_1 + \delta\gamma_2\right),\\ C_5 &= 2k_1\left(\gamma_2^2 - k_1 k_2\right)\theta_0\\ &\quad + \left[\left(k_1 - \gamma_2\right)\left(k_1\gamma_1 - \delta\gamma_2\right) + 2\delta k_1\left(\gamma_2 - k_2\right)\right]\theta_1,\\ C_6 &= 2\delta\left(\gamma_2^2 - k_1 k_2\right), \end{aligned}$$

$$C_7 = 2k_1\left(\gamma_2^2 - k_1k_2\right) + \gamma_1\left(k_1\gamma_1 + \delta\gamma_2\right),$$
$$C_8 = \delta\left(k_1\gamma_1 + \delta\gamma_2\right),$$
$$C_9 = \left(k_1k_2 - \gamma_2^2\right)\left(2k_1\gamma_2 + \delta\gamma_1\right) - \gamma_2\left(k_1\gamma_1^2 + \delta^2 k_2 + 2\delta\gamma_1\gamma_2\right),$$
$$C_{10} = \left(\delta + \gamma_1\right)\left(k_1\gamma_1 + \delta\gamma_2\right)\theta_1 - 2\left(k_1k_2 - \gamma_2^2\right)\left(\delta\theta_0 + k_1\theta_1\right),$$
$$E = k_2 + \frac{C_4\gamma_1}{C} + \frac{C_9}{C},$$
$$E_1 = \frac{C_1a_0 + C_2a_1 + C_3a_2 + C_5s}{C} + \frac{c_1}{2},$$
$$E_2 = \frac{C_6a_0 + C_7a_1 + C_8a_2 + C_{10}s}{C} + \frac{c_1}{2}. \tag{B.1}$$

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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