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INFORMATION SHARING FOR COMPETING SUPPLY CHAINS WITH DEMAND DISRUPTION

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Abstract. We investigate pricing decisions and information value in two competing supply chains, each consisting of one manufacturer and one retailer. Both retailers are engaged in Bertrand retail competition and are endowed with the private information on the disrupted demand. Three information sharing scenarios have been considered, *i.e.*, information sharing in both chains, information sharing in only one chain, and information sharing in neither chain. For each information scenario, there always exists robustness for each manufacturer's production plan. That is, when the disrupted amount of the market demand is sufficiently small, the manufacturer's production plan or the retailer's order quantity will be unchanged. Meanwhile, we also study the information value by comparing these three information scenarios, and find that the information value not only works in one chain directly, but also does in the competing chain indirectly. Through comparative analysis, we find that the retailer is reluctant to share his private information on the disrupted demand with his partner because of the fear of information leakage. Meanwhile, the performance of the whole chain may become worse off if the information of disrupted demand is shared in this chain.

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1. Introduction

Over the last two decades, many types of unpredictable events or disasters, such as terrorist acts, natural calamities, earthquake, economic crises, wars and infectious diseases, are witnessed. When these disasters occur, major business disruptions follow. These disruptions may pose a significant threat to the supply chain management. Supply chain disruption risks, vulnerabilities and uncertainties are now becoming hot issues of interest amongst academics and practitioners. As many supply chain decision-maker strived to improve their financial performance, they implemented various plans or initiatives to increase revenue and reduce cost. These initiatives are powerful and effective in a stable environment with a known market demand, but they have also created longer and more complex global supply chains, which are more vulnerable to business disruptions in a turbulent world [1]. Hence, how to handle disruptions in an efficient and effective way has become increasingly important to the success of supply chain management.

Keywords. Supply chain competition, information sharing, game theory, disruption management, robustness.

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Supply chain disruptions are unanticipated events that disrupt the normal flow of goods and materials within a supply chain and, as a consequence, expose channel members to operational and financial risks [2]. Supply chain disruptions and associated operational and financial risks are the most pressing issue faced by firms in today's competitive global environment. *E.g.*, the explosion in 2012 at Evonik industries factory in Germany caused a global shortage of CDT, a key ingredient of Nylon PA12, which is widely used to make a specialized plastic for manufacturing components across the global automotive industry. The probability of all these unexpected events' occurring is very small; however, the impact is very serious. A representative example is that Ericsson lost 400 million Euros after their supplier's semiconductor plant in New Mexico caught fire in 2000 [3]. Moreover, according to the report from Achilles, large UK manufacturers and average companies lost respectively more than £58 million and £105 000 dealing with the fall-out from supply chain disruptions in 2013. However, new research shows that much of which could have been prevented by using active disruption management.

The existing studies use the term of irregular operation for the dynamic environment with disruptions to distinguish it from that in the stable environment without disruptions, where the decision-makers usually make their decisions as they have planned originally. However, once the unexpected disruption events occur, the original plan may be not optimal for each decision-maker. Generally, the sudden change of demand or other factors will result in extra deviation costs for the decision-makers [4]. With the disruption of market demand, for example, the manufacturer should pay the workers for the overtime work for accelerating production if the demand increases suddenly, or employ a return policy to handle surplus products if the market demand decreases suddenly. Due to deviation costs involved, the decision-makers should re-plan their production or procurement decisions to reduce total costs and improve their financial performance when the market disruption occurs. Therefore, our first goal of this paper is to design and implement a supply chain capable of coping with and recovering from disruptions.

Our paper develops competition models of two chains with the common disrupted market demand. Due to the growing globalization of economy and complex relationships among diverse business partners and competitors, supply chain competition has undergone tremendous changes in the quest to improve profits and efficiency [5]. The traditional mode of company-to-company competition is starting to give way to a new form of chain-to- chain competition. Generally, the chain-to-chain competition is concerned with the competition at the downstream end of two entirely separate chains. Namely, both the product substitutability and horizontal competition exist between both chains. For example, in the computer industry, large computer manufacturers like Dell and Hewlett-Packard routinely have their brand name retail stores. The consumers can purchase their electric appliances, computers and components from the competing retail market, such as monitor, key-board, or electronic components. Additionally, in the retail industry, ordinary complements are usually sold by the brand name retail store to the customers and the substitutes can be obtained from other retail stores. This paper will focus on chain-to-chain competition with different manufacturers selling through their respective retailers that compete for end customers. Therefore, the second goal is to investigate how the performance and the decisions of one chain are affected by the rival chain.

Our paper also complements the literature on supply chain disruption management by considering the asymmetric information. We study a disruption management mode for two identical competing chains, each consisting of one manufacturer and one retailer. Each retailer can take actions that directly affect market competition, whereas each manufacturer designs the contract for her retailer. In the actual operation, the retailers often have better information on the disrupted demand because of their proximity to consumers. Therefore, we assume that the real information on disruption is only known to the retailers. This asymmetry is represented in terms of the manufacturer's uncertainty on the probability distribution of the amount of disrupted demand. Due to the symmetry of supply chains, three information sharing scenarios on the disrupted demand, *i.e.*, information sharing in both chains, information sharing only in one chain and information sharing in neither chain, are considered to investigate the value of information sharing. The third goal is, therefore, to study the information value and illustrate how the information sharing affects the performance of the channel as well as the rival channel.

The remainder of our paper is organized as follows. The next section provides a summary of the relevant literature. Section 3 presents assumptions and notations used in the whole paper. Section 4 studies the supply chain operations under three possible information scenarios. The information value of competing supply chains is investigated in Section 5. In Section 6, experiments are conducted to analyze the sensitivity of the optimal decisions and profits with respect to disruption parameter. The conclusions are given in Section 7. We give all the proofs in Appendix.

2. Literature review

Our paper is closely related to three streams of literature. The first stream of literature concentrates on information asymmetry and information value. The second stream focuses on the horizontal competition of supply chains. The last stream examines the disruption management of supply chain.

2.1. Information asymmetry and information value

In existing literature, asymmetric information is very common in supply chain management and has also received substantial attention [6,7]. The current studies on supply chain management for asymmetric information mainly focus on two sides: cost and demand. For the case of cost asymmetry, channel members always have some of their own private information like the upstream firm's raw material or production costs and the downstream firm's handling costs. For example, Cakanyildirim *et al.* [8] discuss the retailer's preference of the supplier's type under different market conditions, and show that information asymmetry alone does not necessarily induce loss in channel efficiency. Yang *et al.* [9] study the value of supplier's backup production for the manufacturer is not necessarily larger under symmetric information. In the setting of the assembly systems, Fang *et al.* [10] show that when the suppliers' cost distributions become more positively correlated, the suppliers are always worse off, but the assembler is better off. The similar studies on asymmetric cost information can also be found in Özer and Raz [11], Kostamis and Duenyas [12], and Cao *et al.* [13], Hsieh and Kuo [14]. For the asymmetric demand information, Babich *et al.* [15] show the supplier can extract the entire surplus and attain the first-best solution in the limit for the supply chain by using a buyback contract for asymmetric demand information. Gan *et al.* [16] design the optimal menu of commitment-penalty contracts, and Ren *et al.* [17] design a wholesale price contract with a multi-period review strategy profile in governing a long-term repeated interaction within a supply chain. In addition, there are also other various asymmetry-related issues on, *e.g.*, minimum quality standards [18], inventory [19], supplier's reliability [20], retailer's loss aversion [21], financial markets with two risky assets [22], or delivery [23].

However, the above studies on information sharing or asymmetry may not hold in real life. In fact, the players in a supply chain are likely to protect their sales strategies by hiding their private information to their rival chain, which results in the competition between supply chains under asymmetric information [24]. So it is interesting but challenging to study what information to share and how to share it in the competing chains. This paper will investigate how the information structure (information sharing or not) of one chain affects the decisions rival chain, and study information value by comparing three information sharing scenarios on the disrupted demand.

2.2. Horizontal competition of supply chains

Most existing literature assumes that each chain has a single supplier selling to an exclusive buyer, and focuses on how competition influences equilibrium of supply-chain decisions. For example, the earlier study can be found in the seminal work of McGuire and Staelin [25], which concludes that if two supply chains compete fiercely, operating in a decentralized pattern is the dominant strategy. Boyaci and Gallego [26] consider three competition scenarios between the two chains, including the uncoordinated scenario, the coordinated scenario and the hybrid scenario. Ai *et al.* [27] find that return policies have different implications in the presence of chain-to-chain competition as compared to the case of a monopoly chain. The similar studies can be found in

Liu and Xu [28]. The other various competition-related issues, *e.g.*, product quality [29], advertising [30], post-entry [31], environmental protection [32], information value [33] and consumer environmental awareness [34] have been proposed for supply chain management. Unlike these researches, we focus on the effect of different information scenarios on the decisions of supply chains in a competitive environment, rather than on the operations within them.

Most of the existing literature assumes competitive environment with deterministic demand, and few considers how incomplete information affects decision models in competing supply chains. Our exploration is motivated by Ha and Tong [35] and Ha *et al.* [36]. Ha and Tong [35] study contracting and information sharing in two competing supply chains and highlight the importance of contract type as a driver of the value of information sharing and the role of information sharing capability as a source of competitive advantage under supply chain competition. Furthermore, Ha *et al.* [36] design the incentive mechanism for information sharing in competing chains with production technologies that exhibit diseconomies of scale. Differing with their studies, we focus on both the optimal decisions and information value in symmetric competing chains when the demand is disrupted, and study how each manufacturer designs a menu of contract under the environment of both horizontal retail competition and demand disruption.

2.3. Disruption management

Our study is particularly related to the issue on disruption management of supply chain. The current literature on supply chain management that explicitly models the disruption can be classified into two streams. One stream focuses on proactive disruption mitigation including multi-sourcing, expanding capacity, increasing safety stock, improving flexibility, increasing visibility and lining up alternate transportation modes [37, 38], etc.

Another stream, to which our paper belongs, concentrates on disruption recovery. In the disruption-recovery models, the changes to the original plan induced by a disruption may impose considerable deviation costs throughout the system. The thought of disruption-recovery model, aiming at minimizing the deviation of actual operations from intended plans with minimum costs, can provide an effective research between planning and execution to deal with real-time and unpredictable events [39]. The goal of this disruption management is to alleviate the consequences of disruptions and risks or, simply speaking, to increase the robustness of supply chain management. For the disruption-recovery decision, the production plan or the order quantity in the normal operation (*i.e.*, without disruption) is often preferred option to the decision-maker when the change of decision environment is low enough. Otherwise, both the manufacturer and the retailer will need to adjust their decisions correspondingly.

For the single-channel scenario, the abundant theoretical results on the disruption management can be found in the existing literature. For example, Yu and Qi [4] provide an overview of general applications for disruption management for supply chain operation. Yang *et al.* [40] study the problem of recovering a production plan after a disruption, and propose a dynamic programming method for the problem. They find that a pure demand disruption is easy to handle; while a greedy method can be used for a pure cost disruption. Generally speaking, disruptions may result in certain deviation penalties for the change of original production plan. The existing literature on supply chain disruption management mainly concentrates in three ways: supply-related [41, 42], demand-related [43, 44] or miscellaneous risks [45]. The goal of disruption management is to alleviate the consequences of disruptions and risks or, simply speaking, to increase the robustness of supply chain decision. However, there are very few quantitative models for measuring supply chain robustness when the disruption occurs.

On supply chain robustness, Xiao *et al.* [46] investigate incentive mechanism and robustness for a supply chain with symmetric retailers when the demand is disrupted, and find that managerial results differ while different player bears the production deviation cost with different contracts. Chen and Xiao [44] discuss disruption management and robustness of production for a supply chain with a dominant retailer and multiple asymmetric retailers. When the supply is disrupted, Li *et al.* [47] characterize the sourcing strategies of the retailer in supply chain with two competing suppliers. Huang *et al.* [48] develop a two-period pricing and production decision model in a dual-channel supply chain with the demand disruption, and also study the production robustness. When both cost and demand are disrupted simultaneously, Xiao and Qi [49] apply a quantity discount contract to coordinate supply chain with one manufacturer and two competing retailers. Additionally, Bundschuh *et al.* [50], Hatefi and Jolai [51] and Chen *et al.* [52] also discuss the design of a supply chain from the perspective of both reliability and robustness in their researches.

The above literature mostly assumes that the information on the disrupted demand or cost is known to all the channel members. Meanwhile, the existing disruption-recovery models only converge on the single supply chain without considering the effect of information structure of the rival supply chain. However, this assumption is not unreasonable given today's advanced information technology and increasing awareness of the uncertainty risks among managers from the different chains [53]. In a very small number of studies, Lei *et al.* [54] design a menu of contracts to analyze a simple chain when the retailer is endowed with the private information on the disrupted demand. Unlike Lei *et al.* [54], we investigate how the optimal decisions are affected by both different information scenarios and the retail competition.

Compared with the existing literature, our model is new in the following aspects. First, we investigate pricing decisions and information value in two competing chains with the asymmetric information on the disrupted demand. There is little literature considering the information value except Lei *et al.* [54], in which the case of the single supply chain is studied. Second, by comparing analytically and experimentally three information sharing scenarios, we find that information sharing has direct effect in one chain, but also has indirect effect in the rival chain. We offer several new insights to the related literature [35,36]. *E.g.*, we find that there exists robustness for each manufacturer's production plan when the demand is disrupted, and the contract menu will be changed with the level of disruption. The asymmetric information in most cases can distort the manufacturer's original production plan and the wholesale price decision, which may further cause the channel's performance loss. Third, while the majority of papers in this stream concentrate on how to design the contract menu to reveal the asymmetric information that arise within the firm, our focus is on the information value. We find that information sharing in one chain will be good for the manufacturer but bad for her retailer, while it may bring benefit to all the players in the rival supply chain.

3. Problem description

We develop a game model of two competing chains, each consisting of a manufacturer (she) selling a substitutable product to her own retailer (him) only. In our paper, the manufacturers, the retailers, and the chains are indexed by $i = 1, 2$. Two chains are assumed to be identical, except they may have different information scenarios on the disrupted market demand. Both manufacturers have identical marginal production costs, which are denoted as c. Each retailer engages in Bertrand retail competition by determining his retail price (selling quantities) based on the contract designed by his own manufacturer. That is, direct competition exists between the retailers, and the indirect competition exists between the manufacturers. Here, for Bertrand retail competition, we assume that the demand function for retailer i is given as follows.

$$q_i = a - p_i + bp_j, \quad \text{where} \quad i, j = 1, 2, \quad \text{and} \quad i \neq j. \tag{3.1}$$

Where a is denoted as the demand scale, p_i is the market retail price provided by retailer i, q_i is the selling quantity of retailer i and $b$is the substitutability coefficient with $0 < b < 1$. The substitutability coefficient is a measure of the sensitivity of retailer i's sale to the change of retailer j's price, and it also implies the intensity of competition. We investigate the single-period single-purchasing-opportunity newsboy problem when considering the retail competition of supply chains. In our setting, we assume that both manufacturers act as the Stackelberg leaders in their respective chains. Both manufacturers move first separately and simultaneously by setting unit wholesale prices and a production plans, and the retailers then decides how much to order from the manufacturers or how to set their respective retail prices. In addition, we assume the reservation profit of each retailer is zero whether the disruption occurs or not. This assumption is usually used in the supply chain contracting literature [9], and it is common to be used in the contract on the trading quantity for a manufacturer-retailer relationship. When there is not any disruption occurred in the operation, the profit of retailer i can be written as

$$\Pi_{Ri} = (p_i - w_i)(a - p_i + bp_j), \quad \text{and} \quad i = 1, 2. \tag{3.2}$$

From the first-order condition of equation (3.2), we derive the optimal retail price and order quantity of retailer i, which are denoted as $p_i = (a + bp_j + w_i)/2$ and $q_i = (a + bp_j - w_i)/2$, respectively. In addition, the profit of manufacturer i can be denoted as

$$\Pi_{Mi} = (w_i - c)(a - p_i + bp_j), \quad \text{and} \quad i = 1, 2. \tag{3.3}$$

Then, we derive the optimal wholesale price for manufacturer i, denoted as $w_i = (a + bp_j + c)/2$. Therefore, we can obtain the following symmetric equilibriums.

Proposition 3.1. *For normal operation without disruption, the unique equilibrium solutions can be denoted as*

$$p_i^o = (3a + c)/(4 - 3b), \quad w_i^o = (2a + (2 - b)c)/(4 - 3b) \quad \textit{and} \quad q_i^o = (a - (1 - b)c)/(4 - 3b). \tag{3.4}$$

Here, the market scale should satisfy $a > (1 - b)c$. Otherwise, there is no need to satisfy the market demand, since it is not profitable to produce. In practice, the demand is often disrupted unexpectedly by the haphazard event, quality reasons, new technology, promotional events of the player and/or its competitors, etc. With the unpredicted change, each player will adjust his original strategies. For example, the manufacturer may adjust the wholesale price, while the retailer adjusts the retail price. Here, when the disruption occurs, we assume that the demand scale a is changed into $\tilde{a} = a + \Delta a$, where $\Delta a > 0(\Delta a < 0)$ implies that the demand scale increases (decreases).

Unlike the existing literature, the retailers are endowed with some private information on the disrupted demand. The asymmetry is represented in terms of the manufacturer's uncertainty on probability distribution of the disrupted demand, which characterizes the retailer's demand types according to their reliability: high and low. Here, the disrupted amount of demand scale, Δa, is assumed to be a random variable given by

$$\Delta a = \begin{cases} \Delta a_H, \text{ with probability } \beta_H \\ \Delta a_L, \text{ with probability } \beta_L. \end{cases} \tag{3.5}$$

Where Δa_H and Δa_L correspond respectively to the high and low disruption amounts of market demand with $\Delta a_H \geqslant \Delta a_L$ and $\beta_H + \beta_L = 1$. β_H is interpreted as the fraction of high-disruption demand in the market with $\beta_H \in [0, 1]$. Here, $\delta = \Delta a_H - \Delta a_L$is denoted as the degree of information asymmetry. A higher value of $(\Delta a_H - \Delta a_L)$ implies a larger gap between the equilibrium order quantities under symmetric and asymmetric information. The assumption of only two disruption types is a simplification of reality, but it is sufficient to capture the main feature of demand uncertainty in our problem. Similar assumption can be found in Ha and Tong [35], and Lee and Yang [55]. In addition, we denote the disruption type as D throughout the paper, where $D = H \text{ or } L$. The disruption type can be observed by the retailers but not the manufacturers, and we assume that both manufacturers use the same contract. According to the possible information type, each manufacturer provides her retailer with the wholesale price contract. Based on the wholesale price contracts offered, both retailer engage in Bertrand competition by simultaneously and independently determining their respective retail prices. In the following, we will study the value of information sharing. We find that information sharing in one supply chain may have the following two effects: (1) direct effect due to the changes in decisions by the players involved in sharing the information and (2) indirect effect (*i.e.*, spillover effect) due to the changes in decisions by the rival chain.

4. Information scenarios and supply chain operations

This section investigates different information sharing scenarios under a wholesale price contract. The wholesale price contract is very popular in practice and is commonly assumed in the information sharing literature. Since both supply chains are assumed to be identical, information scenarios for the both manufacturers will have three possible outcomes: SS (information sharing in both supply chains), NS (information sharing in only one supply chain), and NN (information sharing in neither supply chain). The corresponding sequence of game can be denoted as follows: (i) each manufacturer independently but simultaneously offers the linear wholesale price contract to her retailer; (ii) the retailers privately observe the disruption type on the changed demand (D, where $D = H$ or L); (iii) based on the contract offered, the retailers engage in Bertrand retail competition by simultaneously and independently determining how to price in their respective retail markets. We can solve this game by employing backward induction technique.

4.1. *SS model*: Information sharing in both supply chains

In this subsection, we assume that the disrupted demand type $D$is known to all the manufacturers and retailers, where $D = H, L$. Given the disruption type, manufacturer i offers a unit wholesale price to retailer i, and retailer i decides his retail price. The unit wholesale price of manufacturer i cannot be observable by the rival, therefore, the manufacturer and the retailer of each supply chain respond directly to the retail price but not the wholesale price of the competing supply chain. Knowing the disrupted demand type (D) and unit wholesale price ($\tilde{w}_{iD}$) and in anticipation of the retail price ($\tilde{p}_{jD}$) in the rival supply chain, retailer i should determine his retail price, denoted as $\tilde{p}_{iD}$, to maximize the profit function as $\tilde{\Pi}_{Ri} = (\tilde{p}_{iD} - \tilde{w}_{iD})(a + \Delta a_D - \tilde{p}_{iD} + b\tilde{p}_{jD})$.

For the symmetric information type, manufacturer i offers a unit wholesale price contract to retailer $i$according to the real disruption type D, where $i = 1, 2$ and $D = H, L$. In the actual operation, the disruption of demand can result in a production deviation for the original plan designed by each manufacturer, and the changed production amount is denoted as $\Delta\tilde{q}_{iD} = \tilde{q}_{iD} - q_i^o$. Generally, there are deviation penalties associated with the difference, which should be included when making the new price and production decisions. For example; (i) $\Delta\tilde{q}_{iD} > 0$ implies that more items should be produced to meet the unplanned increased quantity. With more products to produce to satisfy the increased demand, some measures such as labor overtime, extra machines should be taken, which can induce a higher unit production cost for the manufacturer; (ii) $\Delta\tilde{q}_{iD} < 0$implies that there is some surplus items which will result in an extra cost such as holding cost, processing or handling cost. In either case, the changed demand will cause disruption to the original production plan of manufacturers. That is, the unit wholesale price or the production quantity for manufacturers may usually different from their original plan due to the disruption of the market demand.

Similar to Xiao *et al.* [46], we assume a unit penalty cost for a unit increased quantity, denoted as c_u, and a unit penalty cost for a unit decreased quantity, denoted as c_s. Then, under SS model, the profit of manufacturer i, denoted as $\tilde{\Pi}^{SS}_{Mi}(\tilde{w}_{iD})$, can be written as follows.

$$\max \tilde{\Pi}^{SS}_{Mi}(\tilde{w}_{iD}) = (\tilde{w}_{iD} - c)\tilde{q}_{iD} - c_u(\tilde{q}_{iD} - q_i^o)^+ - c_s(q_i^o - \tilde{q}_{iD})^+. \tag{4.1}$$

Let $(\tilde{q}^{SS}_{iD}, \tilde{w}^{SS}_{iD})$ be the optimal equilibrium solution for the above model. For the information sharing in both chains, we have the following results.

Proposition 4.1. *Under information sharing in both chains, the optimal order quantity of retailer i satisfies*

$$\tilde{q}^{SS}_{iD} \begin{cases} \geqslant q_i^o, & \textit{if} \quad \Delta a_D \geqslant 0 \\ \leqslant q_i^o, & \textit{if} \quad \Delta a_D \leqslant 0. \end{cases}$$

Proofs of all Propositions are given in Appendix B.2. Proposition 4.1 implies that the change of manufacturer i's production plan depends on the disrupted amount of the demand. When the disrupted demand is larger than zero, manufacturer $i$will change her production plan by increasing the production quantity, and *vice versa*. Based on Proposition 4.1, we can derive the optimal equilibrium solutions for SS model.

Proposition 4.2. *For the information sharing in both chains, the optimal equilibrium solutions are as follows, where $i = 1, 2$ and $D = H, L$.*

(i) *If* $\Delta a_L \geqslant (1-b)c_u$, *we have* $\begin{cases} \tilde{q}_{iD}^{SS} = q_i^o + \Delta q(\Delta a_D, c_u) \\ \tilde{w}_{iD}^{SS} = w_i^o + \Delta w(\Delta a_D, c_u); \end{cases}$

(ii) *If* $\begin{cases} \Delta a_H \geqslant (1-b)c_u \\ -(1-b)c_s \leqslant \Delta a_L < (1-b)c_u, \end{cases}$ *we have* $\begin{cases} \tilde{q}_{iH}^{SS} = q_i^o + \Delta q(\Delta a_H, c_u) \\ \tilde{w}_{iH}^{SS} = w_i^o + \Delta w(\Delta a_H, c_u) \end{cases}$

and $\begin{cases} \tilde{q}_{iL}^{SS} = q_i^o \\ \tilde{w}_{iL}^{SS} = w_i^o + \Delta a_L/(1-b); \end{cases}$

(iii) *If* $\begin{cases} \Delta a_H \geqslant (1-b)c_u \\ \Delta a_L < -(1-b)c_s, \end{cases}$ *we have* $\begin{cases} \tilde{q}_{iH}^{SS} = q_i^o + \Delta q(\Delta a_H, c_u) \\ \tilde{w}_{iH}^{SS} = w_i^o + \Delta w(\Delta a_H, c_u) \end{cases}$

and $\begin{cases} \tilde{q}_{iL}^{SS} = q_i^o + \Delta q(\Delta a_L, -c_s) \\ \tilde{w}_{iL}^{SS} = w_i^o + \Delta w(\Delta a_L, -c_s); \end{cases}$

(iv) *If* $-(1-b)c_s \leqslant \Delta a_D < (1-b)c_u$, *we have* $\begin{cases} \tilde{q}_{iD}^{SS} = q_i^o \\ \tilde{w}_{iD}^{SS} = w_i^o + \Delta a_D/(1-b); \end{cases}$

(v) *If* $\begin{cases} -(1-b)c_s \leqslant \Delta a_H < (1-b)c_u \\ \Delta a_L < -(1-b)c_s, \end{cases}$ *we have* $\begin{cases} \tilde{q}_{iH}^{SS} = q_i^o \\ \tilde{w}_{iH}^{SS} = w_i^o + \Delta a_H/(1-b) \end{cases}$

and $\begin{cases} \tilde{q}_{iL}^{SS} = q_i^o + \Delta q(\Delta a_L, -c_s) \\ \tilde{w}_{iL}^{SS} = w_i^o + \Delta w(\Delta a_L, -c_s); \end{cases}$

(vi) *If* $\Delta a_H < -(1-b)c_s$, *we have* $\begin{cases} \tilde{q}_{iD}^{SS} = q_i^o + \Delta q(\Delta a_D, -c_s) \\ \tilde{w}_{iD}^{SS} = w_i^o + \Delta w(\Delta a_D, -c_s). \end{cases}$

The common-used functions are given in Appendix B.1. From Proposition 4.2, each manufacturer should adjust the corresponding production plan and unit wholesale price to her retailer according to the disruption type and the di sruption level. To better understand relationship between the ordering decisions and the corresponding disruption regions, we give the following results.

Corollary 4.3. *The unique equilibrium solutions under SS model satisfy the following results*

$$\begin{cases} \tilde{q}_{iD}^{SS} > q_i^o, & \text{if} \quad \Delta a_D > (1-b)c_u \\ \tilde{q}_{iD}^{SS} = q_i^o, & \text{if} \quad -(1-b)c_s \leqslant \Delta a_D \leqslant (1-b)c_u \\ \tilde{q}_{iD}^{SS} < q_i^o, & \text{if} \quad \Delta a_D < -(1-b)c_s. \end{cases}$$

Corollary 4.3 presents that manufacturer i should increase the extra trading quantity $\Delta q(\Delta a_D, c_u)$when the demand increases greatly, *i.e.*, $\Delta a_D \geqslant (1-b)c_u$; and lower the total trading quantity $|\Delta q(\Delta a_D, -c_s)|$ when the demand decreases greatly, *i.e.*, $\Delta a_D < -(1-b)c_s$. At the same time, we find there is a robust region for the manufacturer's production plan. That is, when the disrupted amount of market demand is sufficiently small, *i.e.*, $-(1-b)c_s \leqslant \Delta a_D \leqslant \quad (1-b)c_u$, each manufacturer will not change her production plan because of the introduce of deviation penalties. The production plan for the changed amount of $-(1-b)c_s \leqslant \Delta a_D \leqslant (1-b)c_u$ has robustness for both disruption types. In addition, with the changed demand, each manufacturer should adjust her unit wholesale price, and increase the unit wholesale price when the demand increases, or lower the unit wholesale price when the demand decreases.

4.2. *NN model*: Information sharing in neither supply chain

In this subsection, we assume that both manufacturers do not know the real disrupted demand type, D, where $D = H, L$. Each manufacturer should charge her retailer with a unit wholesale price, which does not depend on the disrupted demand type. Therefore, we assume that the unit wholesale price charged by manufacturer i is denoted as $\tilde{w}_i$. At the same time, the wholesale price of manufacturer i cannot be observed by manufacturer j. Since each retailer knows the disruption type of market demand, D, in anticipation of the retail price ($\tilde{p}_{jD}$) decided by retailer j, the profit function of retailer i is same as that in SS model, except that $\tilde{w}_{iD}$ is replaced by $\tilde{w}_i$. The optimal retail price and the order quantity of retailer i are denoted respectively as follows:

$$\tilde{p}_{iD} = (a + \Delta a_D + b\tilde{p}_{jD} + \tilde{w}_i)/2 \quad \text{and} \quad \tilde{q}_{iD} = (a + \Delta a_D + b\tilde{p}_{jD} - \tilde{w}_i)/2. \tag{4.2}$$

For the problem of each manufacturer, the unit wholesale price of each manufacturer will be independent of the demand type since she does not know the real disrupted demand type. Therefore, the expected profit of manufacturer i can be written as

$$\max \tilde{\Pi}_{Mi}^{NN}(\tilde{w}_i) = \sum\nolimits_{D=H,L} \beta_D[(\tilde{w}_i - c)\tilde{q}_{iD} - c_u(\tilde{q}_{iD} - q_i^o)^+ - c_s(q_i^o - \tilde{q}_{iD})^+], \text{ and } i = 1, 2. \tag{4.3}$$

Let $\tilde{w}_{iD}^{NN}, \tilde{p}_{iD}^{NN}, \tilde{q}_{iD}^{NN}$ be the equilibrium wholesale price, retail price and order quantity under the demand type D, respectively, where $D = H$ or L and $i = 1$ or 2. Since the decision of manufacturer i is independent of the demand type, the unit wholesale price can be denoted as $\tilde{w}_i^{NN} = \tilde{w}_{iH}^{NN} = \tilde{w}_{iL}^{NN}$.

From equations (4.2) and (4.3), we can derive the following results.

Proposition 4.4. *When neither supply chain has information sharing, the unique equilibrium solution, denoted as* $(\tilde{w}_{iD}^{NN}, \tilde{q}_{iD}^{NN}), i = 1, 2,$ *and* $D = H, L$, *can be denoted as follows.*

(i) *If* $\Delta a_L \geqslant \frac{1-b}{2-b}[2\beta_H\delta + (2-b)c_u$, *we have* $\begin{cases} \tilde{q}_{iD}^{NN} = q_i^o + \Delta q(\Delta a_D, c_u) + \bar{\delta}_{NN}(\Delta a_D, \beta_H) \\ \tilde{w}_{iD}^{NN} = w_i^o + \Delta w(\Delta a_L, c_u) + \frac{2\beta_H\delta}{4-3b}. \end{cases}$

(ii) *If* $\frac{1-b}{2-b}[2\beta_H\delta + (2-b)\Delta c] < \Delta a_L < \frac{1-b}{2-b}[2\beta_H\delta + (2-b)c_u]$, *we have* $\begin{cases} \tilde{q}_{iH}^{NN} = q_i^o + \frac{\delta}{2-b} \\ \tilde{q}_{iL} = q_i^o \\ \tilde{w}_{iD}^{NN} = w_i^o + \frac{\Delta a_L}{1-b}. \end{cases}$

(iii) *If* $\begin{cases} \Delta a_H \geqslant \frac{1-b}{2-b}[-2\beta_L\delta + (2-b)\Delta c] \\ \Delta a_L \leqslant \frac{1-b}{2-b}[2\beta_H\delta + (2-b)\Delta c], \end{cases}$ *we have* $\begin{cases} \tilde{q}_{iD}^{NN} = q_i^o + \Delta q(\Delta a_D, \Delta c) + \bar{\delta}_{NN}(\Delta a_D, \beta_H) \\ \tilde{w}_{iD}^{NN} = w_i^o + \Delta w(\Delta a_L, \Delta c) + \frac{2\beta_H\delta}{4-3b}. \end{cases}$

(iv) *If* $\frac{1-b}{2-b}[-2\beta_L\delta - (2-b)c_s] < \Delta a_H < \frac{1-b}{2-b}[-2\beta_L\delta + (2-b)\Delta c]$, *we have* $\begin{cases} \tilde{q}_{iH}^{NN} = q_i^o \\ \tilde{q}_{iL}^{NN} = q_i^o - \frac{\delta}{2-b} \\ \tilde{w}_{iD}^{NN} = w_i^o + \frac{\Delta a_H}{1-b}. \end{cases}$

(v) *If* $\Delta a_H \leqslant \frac{1-b}{2-b}[-2\beta_L\delta - (2-b)c_s]$, *we have* $\begin{cases} \tilde{q}_{iD}^{NN} = q_i^o + \Delta q(\Delta a_D, -c_s) + \bar{\delta}_{NN}(\Delta a_D, \beta_H) \\ \tilde{w}_{iD}^{NN} = w_i^o + \Delta w(\Delta a_L, -c_s) + \frac{2\beta_H\delta}{4-3b}. \end{cases}$

The common-used functions are given in Appendix B.1. To better understand relationship between the ordering decisions and the corresponding disruption regions, we give the following corollary.

Corollary 4.5. *The unique equilibrium solution under NN model satisfies the following*

$$\begin{cases} \tilde{q}_{iH}^{NN} > q_i^o, & \text{if} \quad \Delta a_H > \dfrac{1-b}{2-b}[-2\beta_L\delta + (2-b)\Delta c] \\ \tilde{q}_{iH}^{NN} < q_i^o, & \text{if} \quad \Delta a_H < \dfrac{1-b}{2-b}[-2\beta_L\delta - (2-b)c_s] \\ \tilde{q}_{iH}^{NN} = q_i^o, & \text{otherwise} \end{cases} \text{ and } \begin{cases} \tilde{q}_{iL}^{NN} > q_i^o, & \text{if} \quad \Delta a_L > \dfrac{1-b}{2-b}[2\beta_H\delta + (2-b)c_u] \\ \tilde{q}_{iL}^{NN} < q_i^o, & \text{if} \quad \Delta a_L < \dfrac{1-b}{2-b}[2\beta_H\delta + (2-b)\Delta c] \\ \tilde{q}_{iL}^{NN} = q_i^o, & \text{otherwise.} \end{cases} \tag{4.4}$$

Unlike SS model, the change of the order quantity is closely dependent on disruption type. In the high disruption type, we will obtain the following insights based on Corollary 4.5. When the demand decreases greatly, *i.e.*, $\Delta a_H < (1-b)[-2\beta_L\delta - (2-b)c_s]/(2-b)$, manufacturer i will decrease the extra trading quantity with the amount of $(|\Delta q(\Delta a_D, -c_s) + \bar{\delta}_{NN}(\Delta a_D, \beta_H)|)$. When the market demand increases greatly, *i.e.*, $\Delta a_H > (1-b)[-2\beta_L\delta + (2-b)\Delta c]/(2-b)$, manufacturer i will increase the extra trading quantity, which is depending on the level of the disruption. Meanwhile, there also exists a robust region for the production plan of each manufacturer when the changed demand is located between these two threshold values. Similarly, we can obtain the changes of the production quantity/order quantity for the case of the low disruption type.

4.3. *NS model*: Information sharing only in chain 2

In this subsection, we assume that the information on the disrupted demand is asymmetric in chain 1, that is, manufacturer 1 does not know the real disrupted demand type D and charges the unit wholesale price as $\tilde{w}_1$, while the disrupted demand information is symmetric in chain 2. In anticipation of the retail price ($\tilde{p}_{2D}$) of retailer 2, the profit function of retailer 1 is the same with that in SS model, except that $\tilde{w}_{1D}$ is replaced by $\tilde{w}_1$. Consequently, the retail price and order quantity of retailer 1 can be denoted as follows, respectively,

$$\tilde{p}_{1D} = (a + \Delta a_D + b\tilde{p}_{2D} + \tilde{w}_1)/2 \quad \text{and} \quad \tilde{q}_{1D} = (a + \Delta a_D + b\tilde{p}_{2D} - \tilde{w}_1)/2. \tag{4.5}$$

Sine we assume that the manufacturer and the retailer of chain 1 respond directly to the retail price of the competing supply chain, we can derive the following profit for manufacturer 1 in anticipation of the retail price ($\tilde{p}_{2D}$) of retailer 2 for each disrupted demand type (D).

$$\max \tilde{\Pi}_{M1}^{NS}(\tilde{w}_1) = \sum\nolimits_{D=H,L} \beta_D[(\tilde{w}_1 - c)\tilde{q}_{1D} - c_u(\tilde{q}_{1D} - q_1^o)^+ - c_s(q_1^o - \tilde{q}_{1D})^+]. \tag{4.6}$$

In chain 2, the information of the disrupted demand is known to manufacturer 2, therefore, the profit function of manufacturer 2 should be

$$\max \tilde{\Pi}_{M2}^{NS}(\tilde{w}_{2D}) = (\tilde{w}_{2D} - c)\tilde{q}_{2D} - c_u(\tilde{q}_{2D} - q_2^o)^+ - c_s(q_2^o - \tilde{q}_{2D})^+. \tag{4.7}$$

For NS model, it is difficult to give the analytical solutions for all disruption cases, and we just present the disruption cases with the production quantity of chain 2 being larger or lower than the normal production quantity, *i.e.*, $\tilde{q}_{2D}^{NS} > q_2^o$ or $\tilde{q}_{2D}^{NS} < q_2^o$. From equations (4.6) and (4.7), we can derive the following

Proposition 4.6. *For NS model, based on* $\tilde{q}_{2D}^{NS} > q_2^o$ *or* $\tilde{q}_{2D}^{NS} < q_2^o$*, the unique equilibrium solution, denoted as* (w_1^{NS}, q_{1D}^{NS}) *and* $(w_{2D}^{NS}, q_{2D}^{NS})$ *with* $D = H,\ L$*, can be written as follows.*

(i) *If* $\Delta a_L \geqslant \dfrac{2(4-3b^2)\beta_H\delta}{8-3b^2} + (1-b)c_u$ *, we have*

$$\begin{cases} \tilde{q}_{1D}^{NS} = q_1^o + \Delta q(\Delta a_D, c_u) - \dfrac{(4-3b^2)}{b}\bar{\delta}_{NS}(\Delta a_D, \beta_H) \\ \tilde{w}_1^{NS} = w_1^o + \Delta w(\Delta a_L, c_u) + \dfrac{2\beta_H\delta}{4-3b} \end{cases}$$

and

$$\begin{cases} \tilde{q}_{2D}^{NS} = q_2^o + \Delta q(\Delta a_D, c_u) + \bar{\delta}_{NS}(\Delta a_D, \beta_H) \\ \tilde{w}_{2D}^{NS} = w_2^o + \Delta w(\Delta a_D, c_u) + 2\bar{\delta}_{NS}(\Delta a_D, \beta_H). \end{cases}$$

(ii) *If* $\max\{A(\beta_H, c_u), (1-b)c_u\} \leqslant \Delta a_L \leqslant \frac{2(4-3b^2)\beta_H\delta}{8-3b^2} + (1-b)c_u$ *and* $\Delta a_H \geqslant \frac{b(4+3b)\delta}{(8-3b^2)(1+b)} + (1-b)c_u$,

we have $\begin{cases} \tilde{q}_{1H}^{NS} = q_1^o + \frac{(4+3b)\delta}{8-3b^2}; \tilde{q}_{1L} = q_1^o; \\ \tilde{w}_1^{NS} = w_1^o + \frac{(4+3b)\Delta a_L + bc_u}{4-3b^2} \end{cases}$

and $\begin{cases} \tilde{q}_{2D}^{NS} = q_2^o + \Delta q_{NS}(\Delta a_L, c_u) - \frac{(2+b)(4-3b)}{2b}\bar{\delta}_{NS}(\Delta a_D, 0) \\ \tilde{w}_{2D}^{NS} = w_2^o + \Delta w_{NS}(\Delta a_L, c_u) - \frac{(2+b)(4-3b)}{b}\bar{\delta}_{NS}(\Delta a_D, 0). \end{cases}$

(iii) *If* $-\frac{2b\beta_H\delta}{8-3b^2} + \frac{(4-3b^2)c_u - b\Delta c}{4+3b} \leqslant \Delta a_L \leqslant \max\{A(\beta_H, c_u), (1-b)c_u\}$

and $\Delta a_H \geqslant \frac{2b\beta_L\delta}{8-3b^2} + \frac{(4-3b^2)c_u - b\Delta c}{4+3b}$,

we have $\begin{cases} \tilde{q}_{1D}^{NS} = q_1^o - \frac{(4-3b^2)}{b}\bar{\delta}_{NS}(\Delta a_D, \beta_H) + B(c_u, \Delta c) \\ \tilde{w}_1^{NS} = w_1^o + \frac{2\beta_H\delta}{4-3b} + C(\Delta a_L, c_u, \Delta c) \end{cases}$

and $\begin{cases} \tilde{q}_{2D}^{NS} = q_2^o + \bar{\delta}_{NS}(\Delta a_D, \beta_H) + B(\Delta c, c_u) \\ \tilde{w}_{2D}^{NS} = w_2^o + 2\bar{\delta}_{NS}(\Delta a_D, \beta_H) + C(\Delta a_D, \Delta c, c_u). \end{cases}$

(iv) *If* $\min\{-(1-b)c_s, A(-\beta_L, -c_s)\} \leqslant \Delta a_H \leqslant \frac{2b\beta_L\delta}{8-3b^2} - \frac{(4-3b^2)c_s + b\Delta c}{4+3b}$

and $\Delta a_L \leqslant -\frac{2b\beta_H\delta}{8-3b^2} - \frac{(4-3b^2)c_s + b\Delta c}{4+3b}$,

we have $\begin{cases} \tilde{q}_{1D}^{NS} = q_1^o - \frac{(4-3b^2)}{b}\bar{\delta}_{NS}(\Delta a_D, \beta_H) + B(-c_s, \Delta c) \\ \tilde{w}_1^{NS} = w_1^o + \frac{2\beta_H\delta}{4-3b} + C(\Delta a_L, -c_s, \Delta c) \end{cases}$

and $\begin{cases} \tilde{q}_{2D}^{NS} = q_2^o + \bar{\delta}_{NS}(\Delta a_D, \beta_H) + B(\Delta c, -c_s) \\ \tilde{w}_{2D}^{NS} = w_2^o + 2\bar{\delta}_{NS}(\Delta a_D, \beta_H) + C(\Delta a_D, \Delta c, -c_s). \end{cases}$

(v) *If* $-\frac{2(4-3b^2)\beta_L\delta}{8-3b^2} - (1-b)c_s \leqslant \Delta a_H \leqslant \min\{-(1-b)c_s, A(-\beta_L, -c_s)\}$

and $\Delta a_L \leqslant -\frac{b(4+3b)\delta}{(8-3b^2)(1+b)} - (1-b)c_s$,

we have $\begin{cases} \tilde{q}_{1H} = q_1^o; \tilde{q}_{1L}^{NS} = q_1^o - \frac{(4+3b)\delta}{8-3b^2} \\ \tilde{w}_1^{NS} = w_1^o + \frac{(4+3b)\Delta a_H - bc_s}{4-3b^2} \end{cases}$

and $\begin{cases} \tilde{q}_{2D}^{NS} = q_2^o + \Delta q_{NS}(\Delta a_H, -c_s) + \frac{(2+b)(4-3b)}{2b}\bar{\delta}_{NS1}(\Delta a_D, 0) \\ \tilde{w}_{2D}^{NS} = w_2^o + \Delta w_{NS}(\Delta a_H, -c_s) + \frac{(2+b)(4-3b)}{b}\bar{\delta}_{NS1}(\Delta a_D, 0). \end{cases}$

(vi) *If* $\Delta a_H \leqslant -\frac{2(4-3b^2)\beta_L\delta}{8-3b^2} - (1-b)c_s$,

$$\textit{we have}\ \begin{cases} \tilde{q}_{1D}^{NS} = q_1^o + \Delta q(\Delta a_D, -c_s) - \frac{(4-3b^2)}{b}\bar{\delta}_{NS}(\Delta a_D, \beta_H) \\ \tilde{w}_1^{NS} = w_1^o + \Delta w(\Delta a_L, -c_s) + \frac{2\beta_H\delta}{4-3b} \end{cases}$$

$$\textit{and}\ \begin{cases} \tilde{q}_{2D}^{NS} = q_2^o + \Delta q\left(\Delta a_D, -c_s\right) + \bar{\delta}_{NS}\left(\Delta a_D, \beta_H\right) \\ \tilde{w}_{2D}^{NS} = w_2^o + \Delta w\left(\Delta a_L, -c_s\right) + 2\bar{\delta}_{NS}\left(\Delta a_D, \beta_H\right). \end{cases}$$

The common-used functions are given in Appendix B.1. From Proposition 4.6, there is no difference for the unit wholesale price between the high and low disruption types since the demand information is not shared between retailer 1 and manufacturer 1. However, manufacturer 2 can provide the more specific and targeted schemes to her retailer.

According to Proposition 4.6, we can derive the following

Corollary 4.7. *Based on* $\tilde{q}_{2D}^{NS} > q_2^o$ *or* $\tilde{q}_{2D}^{NS} < q_2^o$, *the unique equilibrium solution under NS model satisfy the following*

(i) *For chain 1, we have*
(a) $\tilde{q}_{1H}^{NS} > q_1^o$ *for Cases* (i)-(iv) *and* $\tilde{q}_{1L}^{NS} > q_1^o$ *for Case* (i); (b) $\tilde{q}_{1H}^{NS} = q_1^o$ *for Case* (v) *and* $\tilde{q}_{1L}^{NS} = q_1^o$ *for Case* (ii); (c) $\tilde{q}_{1H}^{NS} < q_1^o$ *for Case* (vi) *and* $\tilde{q}_{1L}^{NS} > q_1^o$ *for Cases* (iii)−(vi).

(ii) *For chain 2, we have*
(a) $\tilde{q}_{2D}^{NS} > q_2^o$ *for Cases* (i)−(iii); (b) $\tilde{q}_{2D}^{NS} < q_2^o$ *for Case* (iv)−(vi).

Corollary 4.7 also presents how the disruption degree affects each manufacturer's production plan. Meanwhile, we also find that when the production quantity of chain 2 is larger or lower than the normal production quantity, the production plan of chain 1 also show its robustness for both disruption types.

5. The information value of competing supply chains

Based on three information sharing scenarios investigated in Section 4, here, we will further study how the information sharing in one chain affects the decisions of the this chain as well as the rival chain. The Propositions in this section give the theoretical analysis on the information sharing in terms of two sides. That is, one side is the direct effect of information sharing on supply chain itself and the other side is the spill-over effect on the rival chain. It's important to note that it is very difficult for us to conduct a comprehensive analysis and research for all disruption cases. Here, we just present some comparison among these three models when the disruption amount is large enough, while the rest of comparison will be presented as numerical analysis.

The following Propositions 5.1 and 5.2 give the comparisons of the optimal wholesale/retail price and order quantities among these three models under the condition that the changed amount of disrupted demand is large enough.

Proposition 5.1. *When the disruption amount is large enough,* i.e., $\Delta a_L \geqslant \frac{2(4-3b^2)\beta_H\delta}{8-3b^2} + (1-b)c_u$ *or* $\Delta a_H \leqslant -\frac{2(4-3b^2)\beta_L\delta}{8-3b^2} - (1-b)c_s$, *we have*

$$\text{(i)}\ \begin{cases} \tilde{w}_{1H}^{SS} \geqslant \tilde{w}_{1H}^{NS}, \tilde{w}_{2H}^{SS} \geqslant \tilde{w}_{2H}^{NS} \\ \tilde{p}_{1H}^{SS} \geqslant \tilde{p}_{1H}^{NS}, \tilde{p}_{2H}^{SS} \geqslant \tilde{p}_{2H}^{NS} \end{cases} \textit{and} \begin{cases} \tilde{w}_{1L}^{NS} \geqslant \tilde{w}_{1L}^{SS}, \tilde{w}_{2L}^{NS} \geqslant \tilde{w}_{2L}^{SS} \\ \tilde{p}_{1L}^{NS} \geqslant \tilde{p}_{1L}^{SS}, \tilde{p}_{2L}^{NS} \geqslant \tilde{p}_{2L}^{SS} \end{cases} (\textit{the information is changed in chain } 1);$$

(ii) $\begin{cases} \tilde{w}_{2H}^{NS} \geqslant \tilde{w}_{2H}^{NN}, \tilde{w}_{1H}^{NS} = \tilde{w}_{1H}^{NN} \\ \tilde{p}_{2H}^{NS} \geqslant \tilde{p}_{2H}^{NN}, \tilde{p}_{1H}^{NS} \geqslant \tilde{p}_{1H}^{NN} \end{cases}$ *and* $\begin{cases} \tilde{w}_{1L}^{NN} = \tilde{w}_{1L}^{NS}, \tilde{w}_{2L}^{NN} \geqslant \tilde{w}_{2L}^{NS} \\ \tilde{p}_{1L}^{NN} \geqslant \tilde{p}_{1L}^{NS}, \tilde{p}_{2L}^{NN} \geqslant \tilde{p}_{2L}^{NS} \end{cases}$ (*the information is changed in chain* 2).

From Proposition 5.1, regardless of whether the rival chain has information sharing, we find the following results when the disruption amount is large enough. In the high disruption type, the information sharing of one chain can result in the higher wholesale prices and the higher retail prices for both chains. However, in the low disruption type, the information sharing of one chain will decrease the traded wholesale prices for both chains. For both disruption types, we can give the following explanations: in the higher market demand, it could actually be very profitable for the manufacturer by increasing the unit wholesale price. In the lower market demand, the manufacturer will decrease the unit wholesale price when she knows the real information of the disrupted demand, which can secure the retailer's cooperation in the low-disruption type.

Proposition 5.2. *When the disruption amount is large enough,* i.e., $\Delta a_L \geqslant \frac{2(4-3b^2)\beta_H\delta}{8-3b^2} + (1-b)c_u$ *or* $\Delta a_H \leqslant -\frac{2(4-3b^2)\beta_L\delta}{8-3b^2} - (1-b)c_s$, *we have the following,*

(i) $\begin{cases} \tilde{q}_{1H}^{NS} \geqslant \tilde{q}_{1H}^{SS}, \tilde{q}_{2H}^{NS} \leqslant \tilde{q}_{2H}^{SS} \\ \tilde{q}_{1L}^{SS} \geqslant \tilde{q}_{1L}^{NS}, \tilde{q}_{2L}^{SS} \leqslant \tilde{q}_{2L}^{NS} \end{cases}$ (*the information is changed in chain* 1)*;*

(ii) $\begin{cases} \tilde{q}_{2H}^{NN} \geqslant \tilde{q}_{2H}^{NS}, \tilde{q}_{1H}^{NN} \leqslant \tilde{q}_{1H}^{NS} \\ \tilde{q}_{2L}^{NS} \geqslant \tilde{q}_{2L}^{NN}, \tilde{q}_{1L}^{NS} \leqslant \tilde{q}_{1L}^{NN} \end{cases}$ (*the information is changed in chain* 2).

When the disruption amount is large enough, Proposition 5.2 implies the following the managerial insights: in the low disruption type, whether the competing supply chain has information sharing or not, information sharing in one supply chain can stimulate its retailer to order more products, but reduce the rival retailer's order quantity. In the high disruption type, on the other hand, we can also find that whether the competing supply chain has information sharing or not, the information sharing in one supply chain can result in the less order quantity for its retailer, but it will increase the order quantity of the rival retailer.

Proposition 5.3. *When the disruption amount is large enough,* i.e., $\Delta a_L \geqslant \frac{2(4-3b^2)\beta_H\delta}{8-3b^2} + (1-b)c_u$ *or* $\Delta a_H \leqslant -\frac{2(4-3b^2)\beta_L\delta}{8-3b^2} - (1-b)c_s$, *the profit of each player will satisfy the following*

(i) $\begin{cases} \tilde{\Pi}_{M1}^{SS} \geqslant \tilde{\Pi}_{M1}^{NS}, \tilde{\Pi}_{M2}^{SS} \geqslant \tilde{\Pi}_{M2}^{NS} \\ \tilde{\Pi}_{R1}^{NS} \geqslant \tilde{\Pi}_{R1}^{SS}, \tilde{\Pi}_{R2}^{NS} \leqslant \tilde{\Pi}_{R2}^{SS} \end{cases}$ (*the information is changed in chain* 1)*;*

(ii) $\begin{cases} \tilde{\Pi}_{M1}^{NS} = \tilde{\Pi}_{M1}^{NN}, \tilde{\Pi}_{M2}^{NS} \geqslant \tilde{\Pi}_{M2}^{NN} \\ \tilde{\Pi}_{R1}^{NS} \geqslant \tilde{\Pi}_{R1}^{NN}, \tilde{\Pi}_{R2}^{NS} \leqslant \tilde{\Pi}_{R2}^{NN} \end{cases}$ (*the information is changed in chain* 2).

According to Proposition 5.3, when the disruption amount is large enough, the information sharing in a supply chain will do better to the manufacturer, but at the expense of sacrificing the retailer's interest. For example, $\tilde{\Pi}_{M1}^{SS} \geqslant \tilde{\Pi}_{M1}^{NS}$ and $\tilde{\Pi}_{R1}^{NS} \geqslant \tilde{\Pi}_{R1}^{SS}$ implies that information sharing in chain 1 benefits manufacturer 1 but hurts retailer 1, while $\tilde{\Pi}_{M2}^{NS} \geqslant \tilde{\Pi}_{M2}^{NN}$ and $\tilde{\Pi}_{R2}^{NN} \geqslant \tilde{\Pi}_{R2}^{NS}$ implies that information sharing in chain 2 benefits manufacturer 2 but hurts retailer 2. In addition, we also find that information sharing of one supply chain may bring benefit to the players in the rival supply chain. For example, $\tilde{\Pi}_{M2}^{SS} \geqslant \tilde{\Pi}_{M2}^{NS}$ implies that information sharing in chain 1 will do good to the manufacturer in chain 2, while $\tilde{\Pi}_{R2}^{SS} \geqslant \tilde{\Pi}_{R2}^{NS}$ ($\tilde{\Pi}_{R1}^{NS} \geqslant \tilde{\Pi}_{R1}^{NN}$) implies that information sharing in chain 1 (2) will do good to the retailer in chain 2 (1). In the following, we will study the effect of information sharing in one chain on the performance of both chains. Here, we let $\tilde{\Pi}_{Ci}$ be the total profit of supply chain i, that is, $\tilde{\Pi}_{Ci} = \tilde{\Pi}_{Mi} + \tilde{\Pi}_{Ri}$ with $i = 1, 2$.

Proposition 5.4. *When the disruption amount is large enough,* i.e., $\Delta a_L \geqslant \frac{2(4-3b^2)\beta_H\delta}{8-3b^2} + (1-b)c_u$ *or* $\Delta a_H \leqslant -\frac{2(4-3b^2)\beta_L\delta}{8-3b^2} - (1-b)c_s$*, the profit of each supply chain will satisfy the following*

$$\text{(i)} \begin{cases} \Pi_{C1}^{NS} \geqslant \Pi_{C1}^{NN} \geqslant \Pi_{C1}^{SS}, \\ \Pi_{C2}^{NN} \geqslant \Pi_{C2}^{SS} \geqslant \Pi_{C2}^{NS}, \end{cases} \quad \textit{if} \quad 0 < b \leqslant 1 - \sqrt{3}/3;$$

$$\text{(ii)} \begin{cases} \Pi_{C1}^{NS} \geqslant \Pi_{C1}^{SS} \geqslant \Pi_{C1}^{NN}, & \textit{if} \quad 1 - \sqrt{3}/3 \leqslant b \leqslant 2\sqrt{3-\sqrt{3}}\Big/3 \\ \Pi_{C1}^{SS} \geqslant \Pi_{C1}^{NS} \geqslant \Pi_{C1}^{NN}, & \textit{if} \quad 2\sqrt{3-\sqrt{3}}/3 \leqslant b < 1 \end{cases}$$

$$\textit{and} \begin{cases} \Pi_{C2}^{SS} \geqslant \Pi_{C2}^{NN} \geqslant \Pi_{C2}^{NS}, & \textit{if} \quad 1 - \sqrt{3}/3 \leqslant b \leqslant \sqrt{2 - 2\sqrt{3}/3} \\ \Pi_{C2}^{SS} \geqslant \Pi_{C2}^{NS} \geqslant \Pi_{C2}^{NN}, & \textit{if} \quad \sqrt{2 - 2\sqrt{3}/3} \leqslant b < 1. \end{cases}$$

From Proposition 5.4, we can derive the following managerial insights.

(1) When the competition between both chains is low enough, *i.e.*, $0 < b \leqslant 2\sqrt{3-\sqrt{3}}\Big/3$, we have $\Pi_{C1}^{NS} \geqslant \Pi_{C1}^{SS}$ and $\Pi_{C2}^{SS} \geqslant \Pi_{C2}^{NS}$ with the changed information in chain 1; $\Pi_{C2}^{NN} \geqslant \Pi_{C2}^{NS}$ and $\Pi_{C1}^{NS} \geqslant \Pi_{C1}^{NN}$ with the changed information in chain 2. It implies that information sharing in one supply chain will make this chain worse off, but make the rival chain better off, regardless of whether the information is shared in the rival chain.
(2) When the competition becomes more intense, *i.e.*, $2\sqrt{3-\sqrt{3}}\Big/3 < b < \sqrt{2-2\sqrt{3}/3}$, we have $\Pi_{C1}^{SS} \geqslant \Pi_{C1}^{NS}$ and $\Pi_{C2}^{SS} \geqslant \Pi_{C2}^{NS}$ with the changed information in chain 1; and $\Pi_{C2}^{NN} \geqslant \Pi_{C2}^{NS}$ and $\Pi_{C1}^{NS} \geqslant \Pi_{C1}^{NN}$ with the changed information in chain 2; It implies that information sharing in one chain will be beneficial to both chains when the other supply chain also has the information sharing. On the other hand, information sharing in one chain will make this chain worse off, but benefit the rival chain when this rival chain has no information sharing;
(3) when the competition between chains becomes very fierce, *i.e.*, $\sqrt{2-2\sqrt{3}/3} \leqslant b < 1$, we have $\Pi_{C1}^{SS} \geqslant \Pi_{C1}^{NS}$ and $\Pi_{C2}^{SS} \geqslant \Pi_{C2}^{NS}$with the changed information in chain 1; and $\Pi_{C1}^{NS} \geqslant \Pi_{C1}^{NN}$ and $\Pi_{C2}^{NS} \geqslant \Pi_{C2}^{NN}$ with the changed information in chain 2. Namely, the information sharing in one chain will be beneficial to both chains regardless of whether the disruption information is shared in the rival chain.

From the above analysis, it is not necessarily true that information sharing is better for this chain and worse for the rival chain. In some cases, the performance of the decentralized supply chain may become worse off if the information of disrupted demand is shared in this chain. For example, when the competition between both chains is very low, the direct effect of information sharing on one chain is negative, and its spill-over effect on the rival chain, however, is positive. Due to the symmetry of both chains, we can also draw the conclusion that one chain with information sharing sometimes performs worse than the rival without information sharing. Compared with existing literature, the effect of double marginalization in the decentralized supply chain may be enlarged when considering both the competition and information sharing. For Bertrand competition, the effect of the double marginalization can make the chain less aggressive under the condition of information sharing, while it can make the rival chain more aggressive.

In addition, when both chains have the same information structure, we have: (i) When $0 < b \leqslant 1 - \sqrt{3}/3$, we have $\Pi_{C1}^{NN} \geqslant \Pi_{C1}^{SS}$ and $\Pi_{C2}^{NN} \geqslant \Pi_{C2}^{SS}$; (ii) when $1 > b \geqslant 1-\sqrt{3}/3$, we have $\Pi_{C1}^{SS} \geqslant \Pi_{C1}^{NN}$ and $\Pi_{C2}^{SS} \geqslant \Pi_{C2}^{NN}$. That is, when the intense of the competition is high (low) enough, the performance of each chain with information shared in both chains will be larger (lower) than that with information shared in neither chain. When the level of competition between both chains is larger than a threshold, the distortions of production quantity in the decentralized operation will result in the market output much smaller than the monopoly quantity. Meanwhile, no information sharing in each chain will further aggravate the effect of double marginalization. That is to say, the player's relative cost structure under no information sharing is distorted by the transfer price, which results in less profit for whole chain. However, when the level of competition is low enough, we can draw a completely opposite conclusion, which looks counterintuitive. In fact, when the product substitutability is less than a certain threshold, the distortions of production quantity in the decentralized operation will result in the market output closer to the monopoly quantity, and information sharing will aggravate the effect of the double marginalization.

6. Numerical examples

In this section, we are interested in the effects of different information scenarios and system parameters on the decision and performance of each player. The numerical comparisons illustrate how both information sharing and the demand disruption affect the decisions and expected profits of the players in both competing chains. In the following examples, we assume that the default values of parameters in the model are given as follows:

$$a = 30, \quad c = 10, \quad c_u = 5, \quad c_s = 2, \quad b = 0.5, \quad \beta = 0.4 \quad \text{and} \quad \Delta a_L = 5.$$

For the high-disruption type, the following Figures 1 and 2 illustrate how three different information scenarios affect the order quantity of each retailer and the unit wholesale price of each manufacturer. From both figures, we find that the increase of high-disruption demand will obviously result in the increase of order quantity for each information scenario, while it will also promote both manufacturers to raise their unit wholesale prices. Meanwhile, in the high- disruption type, information sharing yields the less order quantity for the retailer ($\tilde{q}_{1H}^{NS} \geqslant \tilde{q}_{1H}^{SS}$ or $\tilde{q}_{2H}^{NN} \geqslant \tilde{q}_{2H}^{NS}$), but promotes the rival to order more items ($\tilde{q}_{2H}^{NS} \leqslant \tilde{q}_{2H}^{SS}$or $\tilde{q}_{1H}^{NS} \geqslant \tilde{q}_{1H}^{NN}$). From the perspective of the manufacturers, information sharing of one supply chain will increase not only the unit wholesale price in most cases, but also the unit wholesale price of the rival supply chain. That is, under the decentralized operation, sharing information can make the manufacturer obtain more profit by providing a higher unit wholesale price. In addition, among these three information sharing scenarios, we also find that the asymmetric information under NN model will induce each manufacturer to reduce her unit wholesale price to her retailer, which in turn will yield a higher traded quantity between the manufacturer and her retailer.

However, for the low-disruption type, Figures 3 and 4 give the some different managerial insights. First, under the asymmetrical information, the retailer will reduce his order quantity for the low-disruption type even if the amount of the low disrupted demand remains a constant, see the order quantity of retailer 1 in both NS and NN models and the order quantity of retailer 2 in NN model. However, retailer 2 in NS model will increase his order quantity for the low-disruption type when the information of disrupted demand is shared with the manufacturer. That is, the decease of order quantity in chain 1 due to the asymmetrical information will increase the order

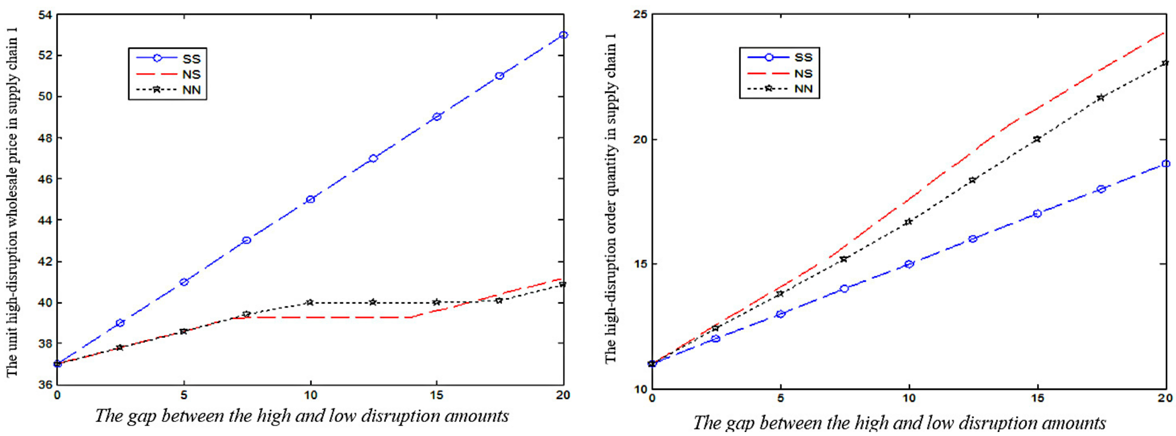

Figure 1. The decision of channel member in chain 1 with the high-disruption type.

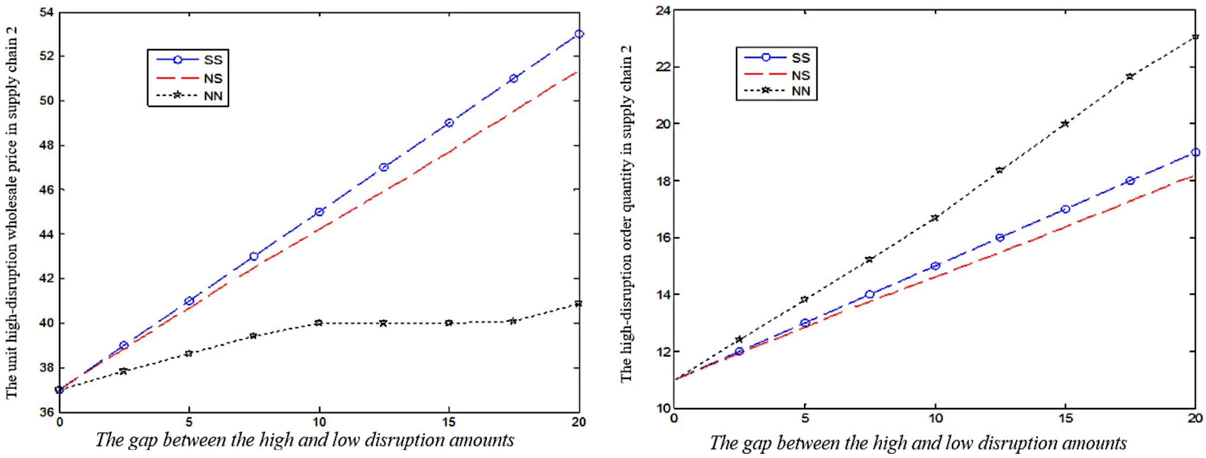

FIGURE 2. The decision of channel member in chain 2 with the high-disruption type.

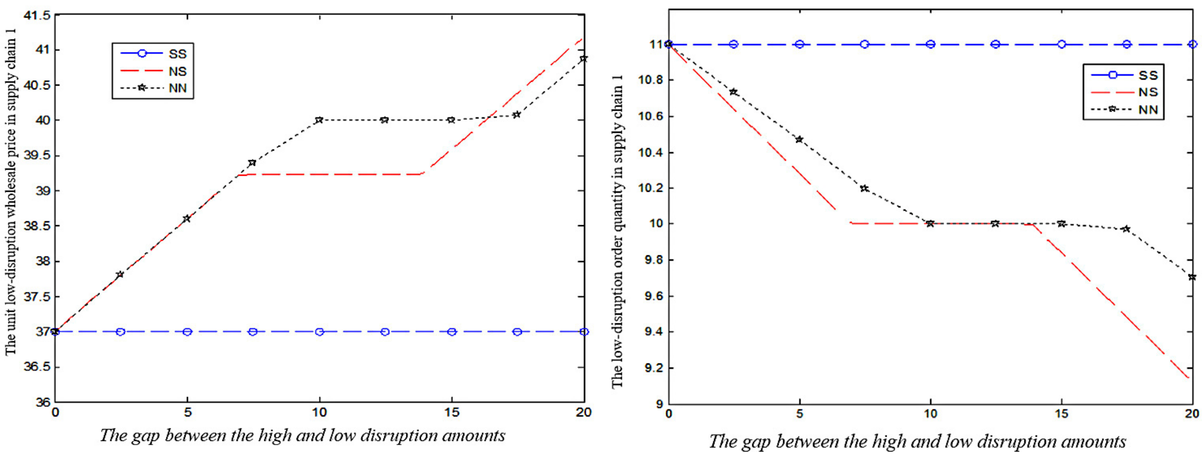

FIGURE 3. The decision of channel member in chain 1 with the low-disruption type.

quantity of the rival supply chain. In addition, in SS model, the retailer's order quantity in the low-disruption type is independent of the demand amount in the high-disruption type due to the symmetrical information between the manufacturer and the retailer.

Second, in the low-disruption type, the unit wholesale price under the information sharing in both chains is always lower than the other two information scenarios. Meanwhile, it is also independent of the demand amount in the high -disruption type. From Figures 3 and 4, the information sharing in chain 1 can reduce the wholesale prices of both supply chains. Differing with the high-disruption type, the manufacturer should decrease the unit wholesale price under the symmetrical information to secure her retailer's cooperation when the disrupted demand in the low type. In addition, the information sharing in chain 2 will reduce its traded wholesale price, but it may increase the wholesale price of chain 1, see the robustness scale of the demand disruption in Figure 3. On the other hand, the information sharing in a chain can promote its retailer to order more items ($\tilde{q}_{1L}^{NS} \leqslant \tilde{q}_{1L}^{SS}$or $\tilde{q}_{2L}^{NN} \leqslant \tilde{q}_{2L}^{NS}$), but induce the rival retailer to order the fewer items ($\tilde{q}_{2L}^{SS} \leqslant \tilde{q}_{2L}^{NS}$or $\tilde{q}_{1L}^{NS} \leqslant \tilde{q}_{1L}^{NN}$) regardless of whether the rival chain has information sharing.

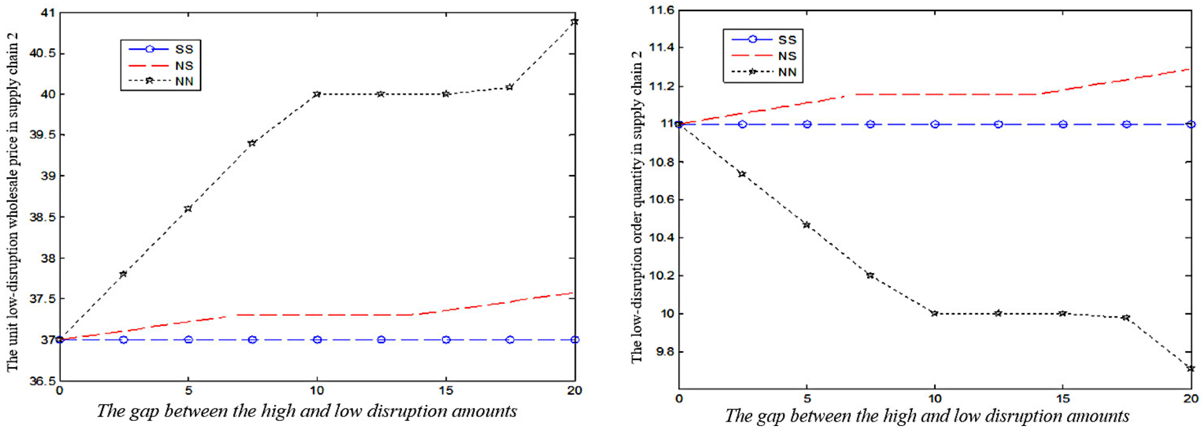

FIGURE 4. The decision of channel member in chain 2 with the low.

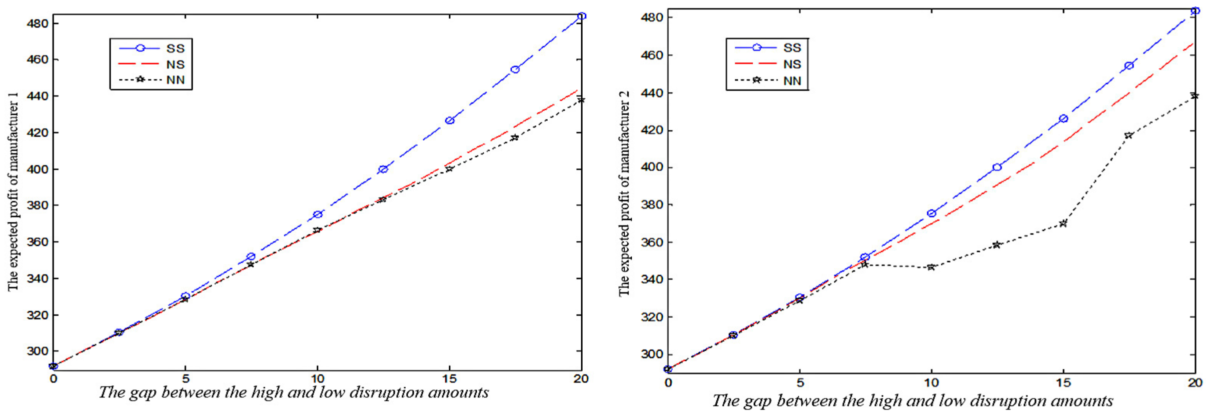

FIGURE 5. The expected profit of each manufacturer under three information sharing scenarios.

In the following, we will investigate how information sharing and the disruption affect the performance of channel members as well as both supply chains.

From Figures 5 and 6, with the increase of the high-disruption demand, each channel member will expect to obtain more profit. In addition, by comparing of these models, we also draw the conclusion that each manufacturer will always obtain more expected profit if one chain has information sharing. In fact, according to these two figures, the information sharing in one chain will benefit not only the manufacturer in this chain ($\Pi_{M1}^{SS} \geqslant \Pi_{M1}^{NS}$ or $\Pi_{M2}^{NS} \geqslant \Pi_{M2}^{NN}$), but also the rival ($\Pi_{M2}^{SS} \geqslant \Pi_{M2}^{NS}$ or $\Pi_{M1}^{NS} \geqslant \Pi_{M1}^{NN}$). On the other hand, the information sharing can cause damages to the retailer in this chain ($\Pi_{R1}^{SS} \leqslant \Pi_{R1}^{NS}$ or $\Pi_{R2}^{NS} \leqslant \Pi_{R2}^{NN}$), while it will benefit the rival retailer ($\Pi_{R2}^{SS} \geqslant \Pi_{R2}^{NS}$ or $\Pi_{R1}^{NS} \geqslant \Pi_{R1}^{NN}$) regardless of whether the rival chain has information sharing or not.

From Figure 7, we find that when the parameter δ is low sufficiently, information sharing in one supply chain has a very small impact on the expected profit of each chain. From Figure 7, we have $\Pi_{C1}^{SS} \leqslant \Pi_{C1}^{NN} \leqslant \Pi_{C1}^{NS}$ for chain 1. That is, information sharing of chain 1 can make this chain worse off; while information sharing of chain 2 can do good to chain 1. Meanwhile, the expected profit of chain 1 under information sharing in both chains is less than that under information sharing in neither chain. Moreover, with the increase of high-disruption demand, the effect of information sharing will become more evident. However, for chain 2, the more

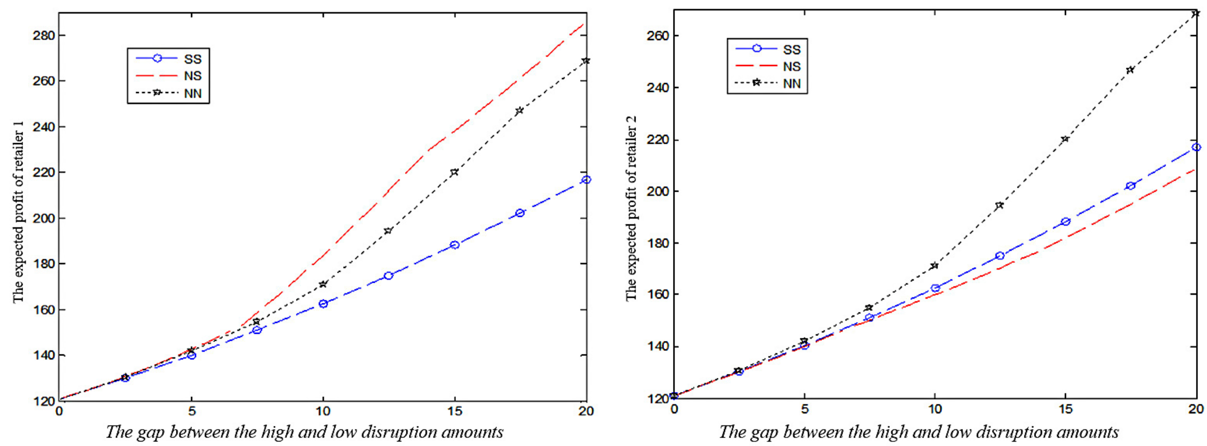

FIGURE 6. The expected profit of each retailer under three information sharing scenarios.

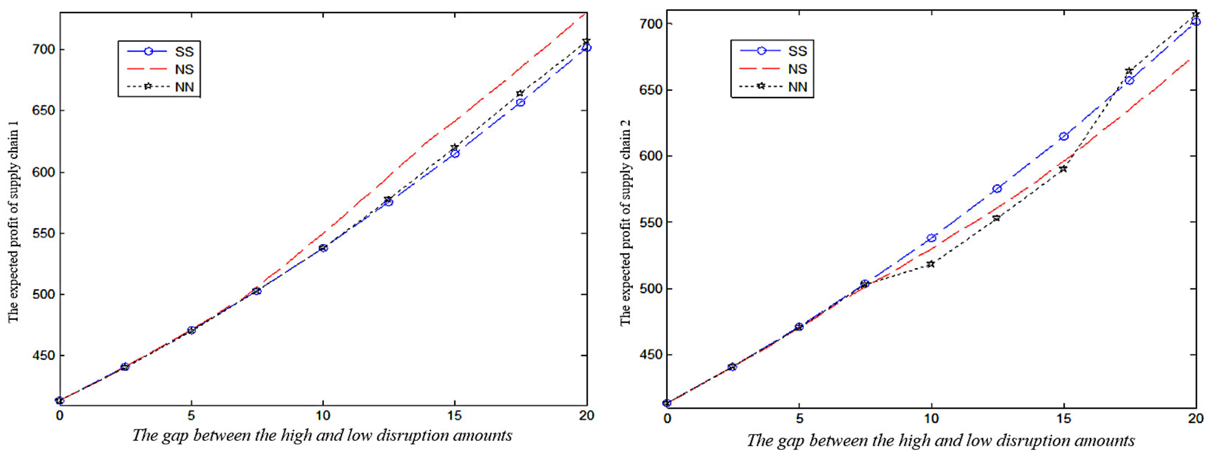

FIGURE 7. The expected profit of each supply chain under three information sharing scenarios.

complex phenomena will be found when the high-disruption demand increases. When the parameter δ is higher than some value, we always have $\Pi_{C2}^{NS} \leqslant \Pi_{C2}^{SS}$, while $\Pi_{C1}^{SS} \leqslant \Pi_{C1}^{NS}$. It implies that under the condition that the information is shared in chain 2, the information sharing in chain 1 will do harm to chain 1, but do good to chain 2. In addition, with the increase of the high-disruption demand, we also find that the profit of chain 2 under NN model is changed from the lowest records to the highest records. It implies that no information sharing will bring the total supply chain more expected profit by decreasing the expected profit of the manufacturer but increasing the information rent for the retailer.

7. CONCLUSIONS

Disruption and the related risk management are major topics in the field of supply chain management and its applications. Our paper investigates the equilibrium decisions of two competing supply chains with the retailers engaging in Bertrand competition when the market demand is disrupted. Unlike the existing literature on disruption management, we assume that the retailers have the private information on the disrupted market demand. Both retailers compete directly in the same retail market and both manufacturers compete indirectly by making information sharing and wholesale pricing decisions to influence the retailers' competition. We consider three possible information sharing scenarios, *i.e.*, information sharing in both chains, information sharing in only one chain, and information sharing in neither chain. We present the major content and the corresponding managerial insights as follows.

(1) *Major content*

◯ For each information sharing scenario, we derive the retailer's optimal pricing strategy and then formulate the contract design problem for each manufacturer.

◯ We compare analytically and experimentally these information sharing scenarios in terms performances of each player and supply chain.

◯ We explore the characteristic of each player's equilibrium policies and study how information sharing affects the decision behavior of each player, and investigate the value of information sharing.

(2) *Managerial insights*

◯ There exists robustness for each manufacturer's production plan when the demand is disrupted, and the contract menu provided by each manufacturer will be changed with the level of disruption.

◯ In most cases, the asymmetric information can distort the manufacturer's original production plan and the unit wholesale price, which may further cause the channel's performance loss. However, the information sharing in the low disruption type will decrease the unit wholesale prices for both channels.

◯ By comparing these three information sharing scenarios, we find that vertical information sharing has direct effect in one chain, but also has indirect effect in the rival chain.

◯ We find that information sharing in a supply chain will do better to the manufacturer, but at the expense of sacrificing the interest of her retailer. Meanwhile, information sharing in one chain may bring benefit to both players in the rival supply chain.

Since disruption management with asymmetric information is a relatively new area of supply chain, there are many research opportunities. There are several extensions of this work that our research could continue. First, our analysis might have some limitations: the decentralized decisions of the players are studied for each supply chain, and it would be meaningful to introduce other contracts to reveal private information of disrupted demand as well as to achieve channel coordination. Second, it would also be interesting to see how our results may change when the wholesale price w_i in supply chain $i$is observable to retailer$j$in the competing supply chain$j$, who would then attempt to infer from w_i the disrupted demand signal that is being shared between the retailer and the manufacturer in supply chain i. Third, a particular demand function is assumed in our paper and that the cross-price effect is symmetric for analytical simplicity. While this demand function has been used widely in existing economics and operation management literatures, one can study whether the qualitative implications can be generalized to other demand functions. Finally, the disrupted amount of the market demand is assumed to be two-type random variable in our paper. However, it would be challenging but beneficial attempt to investigate how each manufacturer designs an incentive mechanism when other general assumptions on the disrupted amount are used.

Appendix A.

The most-used functions in the paper are presented as follows:

$$\delta{=}\Delta a_H - \Delta a_L; \quad \Delta c = \beta_H c_u - \beta_L c_s; \quad \Delta q(\Delta a_D, \tilde{c}){=}\, (\Delta a_D - (1-b)\tilde{c})/(4-3b);$$

$$\Delta w(\Delta a_D, \tilde{c}) = (2\Delta a_D + (2-b)\tilde{c})/(4-3b); \quad \bar{\bar{\delta}}_{NN}(\Delta a_D, \beta_H) = \frac{2(1-b)[(\tilde{a}_D - \tilde{a}_L) - \beta_H(\tilde{a}_H - \tilde{a}_L)]}{(2-b)(4-3b)};$$

$$\Delta q_{NS}(\Delta a_D, \tilde{c}){=}\, ((1+b)\Delta a_D - (1-b^2)\tilde{c})/(4-3b^2); \quad \Delta w_{NS}(\Delta a_D, \tilde{c}) = (2(1+b)\Delta a_D + (2-b^2)\tilde{c})/(4-3b^2);$$

$$\bar{\delta}_{NS}(\Delta a_D, \beta) = \frac{2b[\beta(\tilde{a}_H - \tilde{a}_L) - (\tilde{a}_D - \tilde{a}_L)]}{(4-3b)(8-3b^2)}; \quad \bar{\delta}_{NS1}(\Delta a_D, \beta) = \frac{2b[\beta(\tilde{a}_H - \tilde{a}_L) - (\tilde{a}_H - \tilde{a}_D)]}{(4-3b)(8-3b^2)};$$

$$A(\beta_D, \tilde{c}) = \frac{2(4-3b^2)\beta_D\delta}{8-3b^2} + \frac{(4-3b^2)\Delta c - b\tilde{c}}{4+3b} \quad ; \quad B(\tilde{c}, \Delta c) = \frac{(4+3b)\Delta a_D + b\tilde{c} - (4-3b^2)\Delta c}{16-9b^2};$$

$$C(\Delta a_D, \tilde{c}, \Delta c) = \frac{2(4+3b)\Delta a_D + 2b\tilde{c} + (8-3b^2)\Delta c}{16-9b^2}.$$

Appendix B.

B.1. Proof of Proposition 4.1.

Under information sharing in both chains, each manufacturer can obtain her channel profit by setting the unit wholesale price as $\tilde{w}_{iD} = \tilde{a}_D + b\tilde{p}_{jD} - 2\tilde{q}_{iD}$. Here, we assume that $\tilde{q}^*_{iD} < q^o_i$ when $\Delta a_D > 0$, then we have

$$\begin{aligned}\tilde{\Pi}_{Mi}(\tilde{w}_{iD}) &= (\tilde{w}_{iD} - c)\,\tilde{q}^*_{iD} - c_s\,(q^o_i - \tilde{q}^*_{iD}) \\ &= (\tilde{a}_D + b\tilde{p}_{jD} - 2\tilde{q}^*_{iD} - c)\,\tilde{q}^*_{iD} - c_s\,(q^o_i - \tilde{q}^*_{iD}) \\ &= (a + b\tilde{p}_{jD} - 2\tilde{q}^*_{iD} - c)\,\tilde{q}^*_{iD} + \Delta a_D \cdot \tilde{q}^*_{iD} - c_s\,(q^o_i - \tilde{q}^*_{iD}) \\ &< (a + b\tilde{p}_{jD} - 2q^o_i - c)\,q^o_i + \Delta a_D \cdot q^o_i - c_s\,(q^o_i - q^o_i) \\ &= \tilde{\Pi}_{Mi}(q^o_i).\end{aligned}$$

The inequality holds because the function $(a + b\tilde{p}_{jD} - 2\tilde{q}^*_{iD} - c)\tilde{q}^*_{iD}$ is concave and increasing with $\tilde{q}^*_{iD}$ when $\tilde{q}^*_{iD} < q^o_i$, and $\Delta a_D \cdot \tilde{q}^*_{iD} < \Delta a_D \cdot q^o_i$. Therefore, the optimal trading quantity $(\tilde{q}^*_{iD})$ is not the optimal solution of $\tilde{\Pi}_{Mi}(\tilde{w}_{iD})$, which is contradict with our assumption. Therefore, when $\Delta a_D > 0$, we have $\tilde{q}^*_{iD} \geqslant q^o_i$.

Similarly, we can show that when $\Delta a_D \leqslant 0$, we have $\tilde{q}^*_{iD} \leqslant q^o_i$.

B.2. Proof of Proposition 4.2.

Equation (4.1) can be transformed into the following two cases equivalently.

$$\begin{cases}\max \tilde{\Pi}^{SS}_{Mi}(\tilde{w}_{iD}) = (\tilde{w}_{iD} - c)\tilde{q}_{iD} - c_u(\tilde{q}_{iD} - q^o_i) \\ \tilde{q}_{iD} - q^o_i \geqslant 0\end{cases} \tag{B.1}$$

and

$$\begin{cases}\max \tilde{\Pi}^{SS}_{Mi}(\tilde{w}_{iD}) = (\tilde{w}_{iD} - c)\tilde{q}_{iD} - c_s(q^o_i - \tilde{q}_{iD}) \\ q^o_i - \tilde{q}_{iD} \geqslant 0.\end{cases} \tag{B.2}$$

The KuhnTucker condition of equation (A.1) is

$$\begin{cases}\dfrac{\partial \tilde{\Pi}^{SS}_{Mi}}{\partial \tilde{w}_{iD}} + \mu \dfrac{\partial(\tilde{q}_{iD} - q^o_i)}{\partial \tilde{w}_{iD}} = 0 \\ \mu(\tilde{q}_{iD} - q^o_i) = 0 \\ \mu \geqslant 0 \\ \tilde{q}_{iD} - q^o_i \geqslant 0,\end{cases} \tag{B.3}$$

where μ is the optimal Lagrangian multiplier. Solving equation (A.3), we obtain the following cases.

When $\Delta a_D > (1-b)\,c_u$ it means that the Lagrangian multiplier $\mu = 0$ By differentiating the expected profit of manufacturer i , we can derive that $\tilde{w}^{SS}_{iD} = (\tilde{a}_D + b\tilde{p}^{NS}_{jD} + c + c_u)/2$. Then the optimal production quantity and the unit wholesale price can be denoted as $\tilde{q}^{SS}_{iD} = q^o_i + \Delta q(\Delta a_D, c_u)$ and $\tilde{w}^{SS}_{iD} = w^o_i + \Delta w(\Delta a_D, c_u)$, respectively

When $0 < \Delta a_D \leqslant (1-b)\,c_u$ it means that the Lagrangian multiplier $\mu > 0$ which implies that $\tilde{q}_{iD} - q_i^o = 0$. From the first order condition of the expected profit, we can derive that $\tilde{w}_{iD}^{SS} = (\tilde{a}_D + b\tilde{p}_{jD}^{NS} + c + c_u - \lambda)/2$. According to the KuhnTucker condition, we have $\tilde{q}_{iD}^{SS} = q_i^o$and $\tilde{w}_{iD}^{SS} = w_i^o + \Delta a_D/\,(1-b)$

Similarly, when $\Delta a_D \leqslant -(1-b)\,c_s$, we can derive that $\tilde{w}_{iD}^{SS} = (\tilde{a}_D + b\tilde{p}_{jD}^{NS} + c - c_s)/2$. Therefore, the optimal solution of (B.2) can be denoted as follows: $\tilde{q}_{iD}^{SS} = q_i^o + \Delta q\,(\Delta a_D, -c_s)$ and $\tilde{w}_{iD}^{SS} = w_i^o + \Delta w\,(\Delta a_D, -c_s)$

When $-(1-b)c_s \leqslant \Delta a_D \leqslant 0$, we can derive that $\tilde{w}_{iD}^{SS} = (\tilde{a}_D + b\tilde{p}_{jD}^{NS} + c - c_s + \lambda)/2$. Then, the optimal solution of (B.2) can be denoted as $\tilde{q}_{iD}^{SS} = q_i^o$ and $\tilde{w}_{iD}^{SS} = w_i^o + \Delta a_D/\,(1-b)$

Combining two cases, we can obtain the conclusion of Proposition 4.2.

B.3. Proof of Proposition 4.4.

Similar to proof of Proposition 4.2, equation (4.3) can be transformed into the following four cases

$$\begin{cases} \max \tilde{\Pi}_{Mi}^{NN}\,(\tilde{w}_i) = \beta[(\tilde{w}_i - c)\tilde{q}_{iH} - c_u(\tilde{q}_{iH} - q_i^o)] + (1-\beta)\,[(\tilde{w}_i - c)\tilde{q}_{iL} - c_u(\tilde{q}_{iL} - q_i^o)] \\ \tilde{q}_{iH} - q_i^o \geqslant 0 \\ \tilde{q}_{iL} - q_i^o \geqslant 0; \end{cases} \tag{B.4}$$

$$\begin{cases} \max \tilde{\Pi}_{Mi}^{NN}\,(\tilde{w}_i) = \beta[(\tilde{w}_i - c)\tilde{q}_{iH} - c_u(\tilde{q}_{iH} - q_i^o)] + (1-\beta)\,[(\tilde{w}_i - c)\tilde{q}_{iL} - c_s(q_i^o - \tilde{q}_{iL})] \\ \tilde{q}_{iH} - q_i^o \geqslant 0 \\ q_i^o - \tilde{q}_{iL} \geqslant 0; \end{cases} \tag{B.5}$$

$$\begin{cases} \max \tilde{\Pi}_{Mi}^{NN}\,(\tilde{w}_i) = \beta[(\tilde{w}_i - c)\tilde{q}_{iH} - c_s(q_i^o - \tilde{q}_{iH})] + (1-\beta)\,[(\tilde{w}_i - c)\tilde{q}_{iL} - c_s(q_i^o - \tilde{q}_{iL})] \\ q_i^o - \tilde{q}_{iH} \geqslant 0 \\ q_i^o - \tilde{q}_{iL} \geqslant 0; \end{cases} \tag{B.6}$$

$$\begin{cases} \max \tilde{\Pi}_{Mi}^{NN}\,(\tilde{w}_i) = \beta[(\tilde{w}_i - c)\tilde{q}_{iH} - c_s(q_i^o - \tilde{q}_{iH})] + (1-\beta)\,[(\tilde{w}_i - c)\tilde{q}_{iL} - c_u(\tilde{q}_{iL} - q_i^o)] \\ q_i^o - \tilde{q}_{iH} \geqslant 0 \\ \tilde{q}_{iL} - q_i^o \geqslant 0. \end{cases} \tag{B.7}$$

Note that equation (B.7) means that $\tilde{q}_{iL} > q_i^o > \tilde{q}_{iH}$. From these conditions, we can draw the conclusion that $\Delta a_H < \Delta a_L$. Therefore, it should be removed.

The Kuhn–Tucker condition of equation (B.4) is

$$\begin{cases} \dfrac{\partial \tilde{\Pi}_{Mi}^{NN}}{\partial \tilde{w}_{iD}} + \mu \dfrac{\partial(\tilde{q}_{iH} - q_i^o)}{\partial \tilde{w}_i} + \lambda \dfrac{\partial(\tilde{q}_{iL} - q_i^o)}{\partial \tilde{w}_i} = 0, \\ \mu(\tilde{q}_{iH} - q_i^o) = 0, \\ \lambda(\tilde{q}_{iL} - q_i^o) = 0, \\ \mu \geqslant 0, \lambda \geqslant 0, \\ \tilde{q}_{iH} - q_i^o \geqslant 0, \\ \tilde{q}_{iL} - q_i^o \geqslant 0, \end{cases} \tag{B.8}$$

where $\mu$and λ are the optimal Lagrangian multipliers. Solving equation (B.8), we obtain the following.

When $\Delta a_L \geqslant [2\beta\delta + (2-b)c_u](1-b)/(2-b)$, it means that the Lagrangian multipliers $\mu = 0$ and $\lambda = 0$ From the first order condition of the expected profit, we can derive that

$$\tilde{w}_i^{NN} = [\beta_H(\tilde{a}_H + b\tilde{p}_{jH}) + \beta_L(\tilde{a}_L + b\tilde{p}_{jL}) + c + c_u]/2.$$

Therefore, the optimal production quantity and the unit wholesale price should be

$$\tilde{q}_{iD}^{NN} = q_i^o + \Delta q\left(\Delta a_D, c_u\right) + \bar{\delta}\left(\Delta a_D, \beta\right) \text{ and}$$
$$\tilde{w}_{iD}^{NN} = w_i^o + \Delta w\left(\Delta a_L, c_u\right) + 2\beta\delta/(4-3b), \text{ respectively}$$

When $\Delta a_L < [2\beta\delta + (2-b)\,c_u]\,(1-b)/(2-b)$ it means that the Lagrangian multipliers $\lambda > 0$ and $\mu = 0$ which implies that $\tilde{q}_{iL} - q_i^o = 0$ By differentiating the expected profit of manufacturer i, we can derive that $\tilde{w}_i^{NN} = [\beta_H\left(\tilde{a}_H + b\tilde{p}_{jH}\right) + \beta_L\left(\tilde{a}_L + b\tilde{p}_{jL}\right) + c + c_u - \lambda]/2$. According to the KuhnTucker condition, we can derive that $\tilde{q}_{iH}^{NN} = q_i^o + \delta/(2-b)$, $\tilde{q}_{iL}^{NN} = q_i^o$ and $\tilde{w}_{iD}^{NN} = w_i^o + \Delta a_L/(1-b)$

When $\lambda = 0, \mu > 0$ it implies that $\tilde{q}_{iH} - q_i^o = 0$ and $q_{iL} - q_i^o > 0$ Therefore, we have $\tilde{q}_{iH} < \tilde{q}_{iL}$, which is contradict with the assumption of $\Delta a_H > \Delta a_L$. Therefore, this case should be removed.

When $\lambda > 0, \mu > 0$ it implies that $\tilde{q}_{iH} - q_i^o = 0$ and $\tilde{q}_{iL} - q_i^o = 0$ For this case, we can obtain that $\lambda + \mu$is equal to two different values. Therefore, this case should be removed.

Proofs of equations (B.5) and (B.6) are similar to that of equation (B.4), and here are omitted.

B.4. Proof of Proposition 4.6.

Similar to the proof of Propositions 4.2 and 4.4, equation (4.6) can be also transformed into four cases equivalently. Here, we also give the proof for the following case.

$$\begin{cases} \max \tilde{\Pi}_{M1}^{NS}\left(\tilde{w}_1\right) = \beta[(\tilde{w}_1 - c)\tilde{q}_{1H} - c_u(\tilde{q}_{1H} - q_1^o)] + (1-\beta)\left[(\tilde{w}_1 - c)\tilde{q}_{1L} - c_u(\tilde{q}_{1L} - q_1^o)\right] \\ \tilde{q}_{1H} - q_1^o \geqslant 0 \\ \tilde{q}_{1L} - q_1^o \geqslant 0. \end{cases} \tag{B.9}$$

Since the solution for NS model is very complex, and we only consider two cases of chain 2, *i.e.*, $\tilde{q}_{2D} > q_2^o$ and $\tilde{q}_{2D} < q_2^o$. Similar to the proof of Proposition 4.2, we can also derive $\tilde{w}_{2D}^{NS} = \tilde{a}_D + b\tilde{p}_{1D}^{NS} + c + c_u/2$ for $\tilde{q}_{2D} > q_2^o$ and $\tilde{w}_{2D}^{NS} = \tilde{a}_D + b\tilde{p}_{1D}^{NS} + c - c_s/2$for $\tilde{q}_{2D} < q_2^o$.

Here, the KuhnTucker condition of equation (B.9) can be denoted as follows.

$$\begin{cases} \dfrac{\partial\tilde{\Pi}_{M1}^{NS}}{\partial\tilde{w}_1} + \mu\dfrac{\partial\left(\tilde{q}_{1H} - q_1^o\right)}{\partial\tilde{w}_1} + \lambda\frac{\partial\left(\tilde{q}_{1L} - q_1^o\right)}{\partial\tilde{w}_1} = 0, \\ \mu\left(\tilde{q}_{1H} - q_1^o\right) = 0, \lambda\left(\tilde{q}_{1L} - q_1^o\right) = 0, \\ \mu \geqslant 0, \lambda \geqslant 0, \\ \tilde{q}_{1H} - q_1^o \geqslant 0, \tilde{q}_{1L} - q_1^o \geqslant 0. \end{cases} \tag{B.10}$$

(1) When $\Delta a_L \geqslant \frac{2(4-3b^2)\beta\delta}{8-3b^2} + (1-b)c_u$, the Lagrangian multipliers $\mu = 0$ and $\lambda = 0$ By differentiating the expected profit of manufacturer 1, we can derive that $\tilde{w}_1^{NS} = (\beta_H\left(\tilde{a}_H + b\tilde{p}_{2H}\right) + \beta_L\left(\tilde{a}_L + b\tilde{p}_{2L}\right) + c + c_u)/2$. When $\tilde{q}_{2D} > q_2^o$, we have $\tilde{w}_{2D}^{NS} = (\tilde{a}_D + b\tilde{p}_{1D}^{NS} + c + c_u)/2$. Therefore, the optimal production quantities and the wholesale prices are denoted as $\tilde{q}_{1D}^{NS} = q_1^o + \Delta q(\Delta a_D, c_u) - \bar{\delta}_{NS}(\Delta a_D, \beta_H)(4-3b^2)/b\tilde{w}_{1D}^{NS} = w_1^o + \Delta w\left(\Delta a_L, c_u\right) \quad + 2\beta_H\delta/(4-3b)$ and $\tilde{q}_{2D}^{NS} = q_2^o + \Delta q(\Delta a_D, c_u) + \bar{\delta}_{NS}(\Delta a_D, \beta_H)$, $\tilde{w}_{2D}^{NS} = w_2^o + \Delta w(\Delta a_D, c_u) + 2\bar{\delta}_{NS}(\Delta a_D, \beta_H)$.
When $\tilde{q}_{2D} < q_2^o$, we have $\tilde{w}_{2D}^{NS} = (\tilde{a}_D + b\tilde{p}_{1D}^{NS} + c - c_s)/2$. However, for this condition, we can derive $\tilde{q}_{1L} > q_1^o$ and $\tilde{q}_{2L} < q_2^o$, which will result in the contradiction for the based assumption on disruption scales. Therefore, this case should be removed.

(2) When $\Delta a_L \leqslant \frac{2(4-3b^2)\beta\delta}{8-3b^2} + (1-b)\,c_u$, the Lagrangian multipliers $\lambda > 0$ and $\mu = 0$ which implies that $\tilde{q}_{1L} - q_1^o = 0$ By differentiating the expected profit of manufacturer 1, we can derive that $\tilde{w}_1^{NS} = \frac{\beta_H(\tilde{a}_H + b\tilde{p}_{2H}) + \beta_L(\tilde{a}_L + b\tilde{p}_{2L}) + c + c_u - \lambda}{2}$. When $\tilde{q}_{2D} > q_2^o$, we have $\tilde{w}_{2D}^{NS} = \frac{\tilde{a}_D + b\tilde{p}_{1D}^{NS} + c + c_u}{2}$. Then substituting

$\tilde{w}_1^{NS}$and $\tilde{w}_{2D}^{NS}$ into the functions of $\tilde{p}_{1D}^{NS} = \frac{\tilde{a}_D+b\tilde{p}_{2D}^{NS}+\tilde{w}_1^{NS}}{2}$ and $\tilde{p}_{2D}^{NS} = \frac{\tilde{a}_D+b\tilde{p}_{1D}^{NS}+\tilde{w}_{2D}^{NS}}{2}$, respectively we can derive $\tilde{q}_{1H}^{NS} = q_1^o + \frac{(4+3b)\delta}{8-3b^2}$, $\tilde{q}_{1L}^{NS} = q_1^o$, $\tilde{w}_1^{NS} = w_1^o + \frac{(4+3b)\Delta a_L+bc_u}{4-3b^2}$ $\tilde{w}_{1D}^{NS} = w_1^o + \Delta w\left(\Delta a_L, c_u\right) + \frac{2\beta_H\delta}{4-3b}$, $\tilde{q}_{2D}^{NS} = q_2^o + \Delta q\left(\Delta a_L, c_u\right) - \frac{(2+b)(4+3b)}{2b}\bar{\delta}_{NS}\left(\Delta a_D, 0\right)$ and $\tilde{w}_{2D}^{NS} = w_2^o + \Delta w\left(\Delta a_L, c_u\right) - \frac{(2+b)(4-3b)}{b}\bar{\delta}_{NS}\left(\Delta a_D, 0\right)$. When $\tilde{q}_{2D} < q_2^o$, we have $\tilde{w}_{2D}^{NS} = \tilde{a}_D + b\tilde{p}_{1D}^{NS} + c - c_s/2$. However, for this case, we can derive $\tilde{q}_{1L}^{NS} > q_1^o$ and $\lambda > 0$, which will yield the contradict result for the disruption scales under these two conditions. Therefore, this case should be removed.

(3) When $\lambda = 0$ and $\mu > 0$ it implies that $\tilde{q}_{iH} - q_i^o = 0$ and $\tilde{q}_{iL} - q_i^o > 0$ Therefore, we have $\tilde{q}_{iH} < \tilde{q}_{iL}$, which will result in the contradiction with the assumption of $\Delta a_H > \Delta a_L$. Therefore, this case should be removed.

(4) When $\lambda > 0$ and $\mu > 0$ which implies that $\tilde{q}_{iH} - q_i^o = 0$ and $\tilde{q}_{iL} - q_i^o = 0$ Under this case, we can obtain that $\lambda + \mu$ is equal to two different values. Therefore, this case should be also removed.

The rest results can also be obtained by using the similar mathematical deduction, and here is omitted.

B.5. Proof of Proposition 5.1.

Based on the results presented in Propositions 4.2–4.6, we can derive the following:

(a) When $\Delta a_L \geqslant \dfrac{2(4-3b^2)\beta_H\delta}{8-3b^2} + (1-b)c_u$

(1) For chain 1, we have

$$\tilde{w}_{1H}^{SS} - \tilde{w}_{1H}^{NS} = \frac{2(1-\beta)(\tilde{a}_H - \tilde{a}_L)}{4-3b} > 0,$$

$$\tilde{w}_{2H}^{SS} - \tilde{w}_{2H}^{NS} = \frac{4b(1-\beta)(\tilde{a}_H - \tilde{a}_L)}{(4-3b)(8-3b^2)} > 0,$$

$$\tilde{w}_{1L}^{SS} - \tilde{w}_{1L}^{NS} = \frac{-2\beta(\tilde{a}_H - \tilde{a}_L)}{4-3b} < 0,$$

$$\tilde{w}_{2L}^{SS} - \tilde{w}_{2L}^{NS} = \frac{-4b\beta(\tilde{a}_H - \tilde{a}_L)}{(4-3b)(8-3b^2)} < 0,$$

$$\tilde{p}_{1H}^{SS} - \tilde{p}_{1H}^{NS} = \frac{8(1-\beta)(\tilde{a}_H - \tilde{a}_L)}{(4-3b)(8-3b^2)} > 0,$$

$$\tilde{p}_{2H}^{SS} - \tilde{p}_{2H}^{NS} = \frac{6b(1-\beta)(\tilde{a}_H - \tilde{a}_L)}{(4-3b)(8-3b^2)} > 0,$$

$$\tilde{p}_{1L}^{SS} - \tilde{p}_{1L}^{NS} = \frac{-8\beta(\tilde{a}_H - \tilde{a}_L)}{(4-3b)(8-3b^2)} < 0,$$

and

$$\tilde{p}_{2L}^{SS} - \tilde{p}_{2L}^{NS} = \frac{-6b\beta(\tilde{a}_H - \tilde{a}_L)}{(4-3b)(8-3b^2)} < 0.$$

(2) For chain 2, we have

$$\tilde{w}_{2H}^{NS} - \tilde{w}_{2H}^{NN} = \frac{2(1-\beta)(2+b)(\tilde{a}_H - \tilde{a}_L)}{8-3b^2} > 0,$$

$$\tilde{w}_{2L}^{NS} - \tilde{w}_{2L}^{NN} = \frac{-2\beta(2+b)(\tilde{a}_H - \tilde{a}_L)}{8-3b^2} < 0,$$

$$\tilde{p}_{2H}^{NS} - \tilde{p}_{2H}^{NN} = \frac{4(1-\beta)(\tilde{a}_H - \tilde{a}_L)}{(2-b)(8-3b^2)} > 0,$$

$$\tilde{p}_{1H}^{NS} - \tilde{p}_{1H}^{NN} = \frac{2b(1-\beta)(\tilde{a}_H - \tilde{a}_L)}{(2-b)(8-3b^2)} > 0,$$

$$\tilde{p}_{1L}^{NS} - \tilde{p}_{1L}^{NN} = \frac{-2b\beta(\tilde{a}_H - \tilde{a}_L)}{(2-b)(8-3b^2)} < 0,$$

and

$$\tilde{p}_{2L}^{NS} - \tilde{p}_{2L}^{NN} = \frac{-4\beta(\tilde{a}_H - \tilde{a}_L)}{(2-b)(8-3b^2)} < 0.$$

(b) When

$$\Delta a_H \leqslant -\frac{2(4-3b^2)\beta_L\delta}{8-3b^2} - (1-b)c_s,$$

we have the same comparison results.

Therefore, we can derive Proposition 5.1.

B.6. Proofs of Propositions 5.2 and 5.3.

By performing some algebraic manipulation, we can derive these results.

B.7. Proof of Proposition 5.4

(i) The total profit of chain 1 can be denoted as $\tilde{\Pi}_{C1} = \tilde{\Pi}_{M1} + \tilde{\Pi}_{R1}$. By comparing the total profit of chain 1 under three different information scenarios, we have the following

$$\tilde{\Pi}_{C1}^{NS} - \tilde{\Pi}_{C1}^{NN} = \tilde{\Pi}_{R1}^{NS} - \tilde{\Pi}_{R1}^{NN} \geqslant 0;$$

$$\tilde{\Pi}_{C1}^{SS} - \tilde{\Pi}_{C1}^{NS} = \frac{-2\beta\,(1-\beta)\,(27b^4 - 72b^2 + 32)(\tilde{a}_H - \tilde{a}_L)^2}{(4-3b^2)^2(8-3b^2)^2};$$

and

$$\tilde{\Pi}_{C1}^{SS} - \tilde{\Pi}_{C1}^{NN} = \frac{-2\beta\,(1-\beta)\,(3b^2 - 6b + 2)(\tilde{a}_H - \tilde{a}_L)^2}{(4-3b)^2(2-b)^2}.$$

(ii) Comparing the total profit of chain 2 under three different information scenarios, we have

$$\tilde{\Pi}_{C2}^{SS} - \tilde{\Pi}_{C2}^{NS} = \frac{12\beta\,(1-\beta)\,b(8-b-3b^2)(\tilde{a}_H - \tilde{a}_L)^2}{(4-3b)^2(8-3b^2)};$$

$$\tilde{\Pi}_{C2}^{SS} - \tilde{\Pi}_{C2}^{NN} = \frac{-2\beta\,(1-\beta)\,(3b^2 - 6b + 2)(\tilde{a}_H - \tilde{a}_L)^2}{(4-3b)^2(2-b)^2};$$

and

$$\tilde{\Pi}_{C2}^{NS} - \tilde{\Pi}_{C2}^{NN} = \frac{-2\beta\,(1-\beta)\,(3b^4 - 12b^2 + 8)(\tilde{a}_H - \tilde{a}_L)^2}{(8-3b^2)^2(2-b)^2}.$$

By performing some algebraic manipulation, we can derive main profit comparison results as presented in Proposition.

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