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Drop-Shipping and Backup-Sourcing Strategies Under the Risk of Supply Disruption

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ABSTRACT In recent years, an increasing number of e-retailers have adopted drop-shipping strategy to save logistics costs, and used backup-sourcing strategy to mitigate supply risks. However, the existing literature ignores the significant relationship between the two strategies. In this study, we develop a multi-stage game-theoretical model to investigate the optimal procurement decisions for an e-retailer who can activate both drop-shipping and backup-sourcing strategies. Specifically, our model considers the e-retailer sourcing some units of a product from a supplier to meet the random demand of online customers. The units of the product are held by the supplier, and then are directly shipped to the customers from the supplier side (i.e., drop-shipping strategy). However, there is disruption risk for the supplier; thus, after the randomness of the supplier is realized, the e-retailer can urgently order some units of the product from an expensive but perfectly reliable outside option (i.e., backup-sourcing strategy). We examine the optimal order decisions of the e-retailer and the optimal wholesale price decision of the supplier. Our study shows that for the retailer, the activation of both backup-sourcing and drop-shipping strategies increases its profit, and there is substitutability between the two strategies. For the supplier, the implementation of the drop-shipping (backup-sourcing) strategy increase (decreases) its profit, but the drop-shipping and backup-sourcing are complementary strategies. For the supply chain, when the logistics cost is low or high and the backup-sourcing cost is low, the backup-sourcing and drop-shipping are complementary strategies, whereas in other cases, they are substitutive strategies. Our study not only brings some academic contributions to supply chain management, but also provides significant management insights for the operational practice in terms of drop-shipping and backup-sourcing.

INDEX TERMS Supply chain management, drop-shipping, backup-sourcing, supply risk.

I. INTRODUCTION

A variety of emergencies, such as natural disasters, political unrest, terrorist attacks, worker strikes, technical failures, financial problems, and shortage of raw materials, etc., may pose supply disruption [1]–[3], [38]. Compared with traditional industries, the e-commerce industry is more vulnerable to the risk of supply disruption due to the greater globalization and looser management of supply chains [4]. For example, according to a survey of Accenture, the e-commerce industry has a 67% delivery failure rate during major holidays, such as Christmas [5]. To cope with the risk of supply disruption, backup-sourcing has become one of the most common strategies for online retailers. For instance, in January 2020, the suppliers located in Hubei Province of China suffered disruption due to the severe COVID-19 epidemic and the corresponding road closure measure from the local government; then, the Meituan Fresh,

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a famous online fresh product retailer of China, quickly purchased a great number of fresh agricultural products from backup suppliers located in Shandong province with lighter epidemic to ensure that consumers' demand could be met (finance.sina.com). The backup-sourcing strategy has also been widely adopted by many e-retailers such as Missfresh and JD.com (finance.sina.com).

In addition to supply risk, cost is another core issue that e-commerce enterprises need to consider. As a result, a strategy called "drop-shipping" has been favored by an increasing number of online retailers and suppliers. In drop-shipping, an e-retailer does not keep stock but instead forwards orders to a supplier, who then prepares and ships the orders directly to the end customers [5], [11]. Due to the advantage of this strategy in saving logistics costs, about 22% -33% of online retailers, such as Zappos, Cooking, Spun and Doba, adopt drop-shipping as their primary order fulfillment method [11].

In recent years, an increasing number of online retailers have activated drop-shipping strategy to save logistics costs, and used backup-sourcing strategy to mitigate the risk of supply disruption. For example, Salehoo, a world-famous drop-shipping platform, has more than 8,000 qualified suppliers. The platform provides a list of suppliers for each product so that when a retailer encounters the shortage from her primary supplier, she can select other suppliers from the list for backup [6]. To take another example, China's well-known online food retailer "Benlai" has involved a large number of physical convenience stores and fruit/vegetables supermarkets as its suppliers. If a customer places an order, the retailer will ask the nearest supplier to deliver directly to the customer. Moreover, once the supplier closest to the customer is out of stock, the second nearest supplier (i.e., the backup supplier) can quickly make up the goods (money.163.com). Thus, motivated by operational examples, we investigate the drop-shipping and backup-sourcing strategies for e-commerce related supply chain under the risk of supply disruption.

Although there is rich literature that investigates drop-shipping strategy (e.g., [4]–[7], [9]–[11]) or backup-sourcing strategy (e.g., [12]–[21]), there is little literature considering both. To explore the strategic usage of drop-shipping and backup-sourcing under supply risk, we propose the following model. Consider an e-retailer sourcing some units of a product from a supplier to meet the random demand of online customers. The units of the product are always held by the supplier, and then are directly shipped to the end customers from the supplier side (i.e., drop-shipping strategy). However, there is a disruption risk of the supplier's supply. To mitigate this risk, after the randomness of the supplier's supply is realized, the e-retailer can urgently order some units of the product from a perfectly reliable outside option with a higher cost (i.e., backup-sourcing strategy).

Our model sheds light on the following research questions. First, for the online retailer, does the drop-shipping strategy strengthen or weaken the value of the backup-sourcing strategy on risk mitigating? Our research shows that the implementation of both the two strategies increases the profit of the retailer. However, for the retailer, the backup-sourcing strategy reduces the value of drop-shipping strategy, and vice versa. Second, for the supplier, how does the backup-sourcing strategy affect the value of the drop-shipping strategy on cost-saving? We find that the implementation of the drop-shipping strategy increases the supplier's profit; whereas the usage of the backup-sourcing strategy decreases that. Furthermore, for the supplier, the backup-sourcing strategy increases the value of the drop-shipping strategy, and vice versa. Third, for the supply chain, what is the relationship between the two strategies? Interestingly, our analysis shows that for the supply chain, the two strategies are either substitutive when the logistics cost is low or high and the backup-sourcing cost is low, or complementary when the opposite is the case. Based on the above important research questions and interesting results, this study not only brings academic contributions to supply chain management, but also provides significant management insights for the operation management of e-commerce enterprises.

The rest of this paper is organized as follows. Section II reviews the related literature. Section III presents the model description. Section IV provides the optimal solution of the model and the decision analysis of the supply chain members. Section V shows the values of the drop-shipping strategy and backup-sourcing strategy. We extend our model in Section VI and conclude this study in Section VII. All the proofs are included in the Appendix.

II. LITERATURE REVIEW

In previous studies, there are two streams of literature related to this paper. The first stream of literature is concerned with the drop-shipping strategy. Khouja (2001) analyzes the advantage of the drop-shipping strategy on cost saving and the disadvantage of that on uncontrollable logistics [7]. Netessine and Rudi compare three strategies for an online retailer, i.e., holding inventory, drop-shipping, and a mixture of the two, and obtain the dominant condition for each of the three strategies [8]. Yao *et al.* design a revenue-sharing mechanism for a drop-shipping supply chain, and find that the mechanism not only encourages the supplier to improve its reliability, but also allows the supplier to voluntarily share its private cost information [4]. Gan *et al.* investigate the commitment-penalty contract for a drop-shipping supply chain in which the online retailer has private information about demand [9]. Chiang and Feng examine a joint optimization decision-making problem in the EOQ model for a retailer who uses the drop-shipping strategy [10]. Cheong *et al.* study the impact of opacity of inventory information on the supply chain performance when the drop-shipping strategy is activated, and find that the retailer is more likely to underestimate the inventory of the manufacturer than overestimate that; in addition, the opacity has greatly increased the operating costs of the retailer and the manufacturer, and this effect is more significant for the former [5]. Yu *et al.* analyze the decision-making issue in which a manufacturer uses dual-channel (i.e., online and offline) and needs to determine whether to adopt drop-shipping strategy or traditional strategy (i.e., the retailer holding inventory) on the online channel; the authors find that the manufacturer only adopt drop-shipping strategy when the online retailer faces a small market size [11]. Zeng *et al.* investigate the channel choice between drop-shipping and traditional channel in a supply chain including a wholesaler and multiple financially constrained e-retailers; the authors find that the wholesaler always provides two channel options conditionally under partial trade credit but may offer only one supply chain structure under full trade credit [34]. Ma and Jemai examine a single-period inventory model in which the store inventory can be used to fulfill both offline demand and online demand, and the drop-shipping is used as an additional option for online sale; they analyze two rationing policies for store inventory, i.e., the fixed-portion policy and the threshold policy, and find that there exists an optimal order quantity for store inventory and an optimal stock rationing level below which the manager starts to use drop-shipping for online demand [33]. Shi *et al.* consider a dual-channel supply chain consisting of a manufacturer, an online retailer, and a physical store, where the online order can be fulfilled by either the traditional wholesale contract or the drop-shipping contract; the authors find that when the matching probability of the product and the cost of travel to the physical store are relatively low, drop-shipping contract is the only option. They also show that no matter what kind of contract is signed, the online retailer can benefit from the unbalanced bargaining power of dual-channel retailers [32]. Different from the previous literature on drop-shipping, this study considers supply risk in the drop-shipping supply chain.

The second stream of literature focuses on backup-sourcing strategy under supply risk. Tomlin studies a strategy selection problem (i.e., determining whether to hold excessive inventory or implement backup-sourcing) for a firm who faces the supply disruption risk from the primary supplier, where the backup supplier has higher cost than the primary supplier but is perfectly reliable; the author analyzes the dominant condition for each of the two strategies [12]. Kouvelis and Li investigate the backup-sourcing strategy for a buyer who faces the random lead time from its primary supplier [13]. Hou *et al.* explore a buyback contract between a buyer and a backup supplier when the buyer faces the risk of supply disruption from its primary supplier [14]. Hou and Zhao consider a supply chain involving one retailer and two suppliers, i.e., a main supplier and a backup supplier, where the backup supplier can be used as a regular provider or a stand-by source, and the backup contract with penalty scheme is proposed to cope with the supply disruption (from the main supplier) and the demand uncertainty [37]. Chen and Yang investigate a periodically reviewed inventory system with backup options, in which the expensive backup supplier with limited capacity can be activated when the primary supplier suffers from disruption [15]. Considering that the contract supplier has a random yield, Chen and Xiao examine the backup-sourcing strategy for the buyer and the production plan for the supplier; in addition, the value of backup-sourcing strategy is also investigated [16]. Zeng and Xia design a revenue-sharing contract for backup-sourcing of a buyer, and find that the contract not only responds to the supply disruption risk from the primary supplier, but also encourages the backup supplier to reserve capacity for the buyer [17]. Guo *et al.* study a procurement problem in which the primary supplier suffers from both random disruption and random yield, and analyze the impact of these two different risks on regular and backup-sourcing decisions [18]. Kamalahmadi and Parastb evaluate the effectiveness of a combination strategy with holding inventory, backup-sourcing, and protecting suppliers in mitigating supply risk [19]. Li *et al.* consider a supply chain including a manufacturer and a supplier with supply disruption, and propose two dynamic mitigative approaches; that is, a dynamic reactive strategy for a non-prevention system named passive-backup, and a dynamic combination strategy that contains reactive and proactive strategies for the prevention system named recovery-backup [35]. In the case of the major supplier's disruption risk, Yin and Wang compare three different backup-sourcing strategies for the manufacturer, i.e., advance purchase, reservation, and contingency purchase; they find that the manufacturer selects the advance purchase strategy when the disruption risk is high, reservation strategy when the disruption risk is moderate, and contingency purchase strategy when the disruption risk is low [20]. Gao *et al.* study three strategies (i.e., safety stock, strategic reserve, and backup-sourcing) for a manufacturer to mitigate the supply disruption risk [3]. Considering both instant and delaying consumers, Du and Jiang compare two risk mitigating strategies, i.e., backup-sourcing and reliability improvement, and analyze the dominant condition of each of the two strategies [21]. He *et al.* examine a make-to-stock production-inventory system where the manufacturer may suffer supply disruption; the authors forecast the post-disruption customer behavior, propose dynamic backup-sourcing strategy, and derive the optimal sourcing time [36]. Different from previous research, our study is, to the best of our knowledge, the first to examine the strategic combination of drop-shipping and backup-sourcing under supply risk.

III. MODEL

A. MODEL DESCRIPTION

Consider an e-retailer selling a product to the customers of an offshore market through an e-commerce platform. The market demand D faced by the retailer is random and follows the uniform distribution on $[0, d]$ (see, [22]–[25]).[1] The market is fully competitive; thus, the market price p of the

[1] We will extend our model in Section VI to the situation where D follows general distribution.

product is exogenous (see, [7], [9], [23], [26]).[2] In order to meet the demand, the retailer needs to order the product from a supplier. For convenience, this order is referred to as the regular order. The supplier firstly determines the unit wholesale price w and then the retailer determines the regular order quantity Q_r. After getting the regular order, the supplier starts to produce the product. Assume the unit production cost of the supplier is c (e.g., [40]); thus, the total production cost is cQ_r. However, the supply of the supplier is unreliable due to various potential factors such as natural disasters, terrorist attacks, technical failures, and worker strikes, etc. This unreliability is reflected in the disruption risk; thus, as with previous studies (e.g., [27]–[29]), we assume that the supplier's fulfillment rate δ follows the distribution (0, 1), i.e.,

$$\delta = \begin{cases} 1, & \textbf{with probability } a \\ 0, & \textbf{with probability } 1-a \end{cases}$$

where $0 < a < 1$. Note that a is the probability of successful delivery by the supplier; then, similar to previous studies (e.g., [27]–[29]), we define a as the reliability of the supplier. As a result, the quantity actually supplied by the supplier is δQ_r, and the retailer needs to pay $\delta w Q_r$ (that is, once the supply fails, the retailer pays 0 to the supplier).

In order to save the cost of logistics, the retailer and the supplier adopt the mode of drop-shipping; that is, after each purchase is placed by a customer, the retailer transmits corresponding information (e.g., the address of the customer, the purchase quantity, etc.) to the supplier, and then the supplier directly delivers the product to the customer. We assume that the unit logistics cost of the delivery is c_l, which is paid by the retailer. This drop-shipping strategy is very common in both theoretical research (e.g., [4], [5], [7]) and operational practice (e.g., Amazon and Tmall, which are mentioned in [11]).

To mitigate the disruption risk from the supplier, after the supplier has finished the production (i.e., after the retailer has observed the realized δ), the retailer can urgently order some units of the product from a nearby outside option (e.g., a spot market or a short-term cooperative supplier). For convenience, this order is referred to as the backup order. Suppose the unit cost of the backup order is r. The retailer needs to determine the backup order quantity Q_b. The units of product from the backup order will be delivered to customers by the retailer, and the unit logistics cost will be also c_l. Since the backup source is near the retailer, the logistics cost of backup-sourcing is assumed to be zero.

Finally, the retailer sells the product through the e-commerce platform. Unsold units are discarded, and unsatisfied demand is lost. The timeline of the events is shown in Figure 1.

[2] On online retail platforms, consumers can easily compare the retail prices of products. As a result, the retail prices of similar products are almost the same; in other words, a retailer has little flexibility to make decisions about product price. Thus, we adopt the classic assumption of the newsvendor model; that is, we assume that the demand for the product is random, and the price of the product is exogenous. This assumption is very common in the studies related to the online retail market (e.g., [4], [5], [7], [9], [33], [34]).

To investigate the value of the drop-shipping strategy, we also need to examine the scenarios (i.e., Scenarios 1 and 3 mentioned later) in which the drop-shipping strategy is not activated. In these scenarios, the supplier needs to deliver the yielded units of the product to the retailer, and then the retailer delivers them to customers. Since the supplier and the retailer are geographically far apart, without loss of generality, we assume the unit logistics cost from the supplier to the retailer in the traditional mode as c_l. To avoid meaningless discussions, two assumptions are made as follows:

Assumption 1: $p > r + c_l$. This assumption implies that the unit (market) price of the product (i.e., p) is higher than the sum of the unit backup order cost (i.e., r) and unit delivery cost (i.e., c_l). This assumption is to ensure that the backup-sourcing of the retailer is profitable.

Assumption 2: $r > c/a + c_l$. This assumption means that the unit backup order cost (i.e., r) is greater than the sum of the expected unit production cost of the supplier (i.e., c/a) and unit delivery cost (i.e., c_l). If this assumption is not held, in the scenarios where the drop-shipping strategy is not used (i.e., Scenarios 1 and 3 mentioned later), the retailer will always use backup order to meet the demand, and the regular order cannot be activated.

B. NOTATION

Table 1 shows the main variables and parameters used in our study.

TABLE 1. A list of notations.

Notation	Description
p	Market price
d	Upper bound of the demand
D	The random demand faced by the retailer, which follows $U[0, d]$
Q_{ri}	Regular order quantity determined by the retailer in Scenario i
Q_{bi}	Backup order quantity determined by the retailer in Scenario i
δ	Random yield of the supplier, which follows the (0-1) distribution
c	Unit production cost of the supplier
c_l	Unit logistics cost of the delivery
r	Unit cost of the backup order
a	Reliability of the supplier
w_i	Unit wholesale price determined by the supplier in Scenario i
π_i^M	Expected profit of the supplier in Scenario i
π_i^R	Expected profit of the retailer in Scenario i

IV. DECISION ANALYSIS FOR THE SUPPLY CHAIN

In this section, we discuss the optimal decisions for the supplier and the retailer in the following 4 scenarios. In Scenario 1, neither the drop-shipping strategy nor the backup-sourcing strategy is activated (see, subsection A).

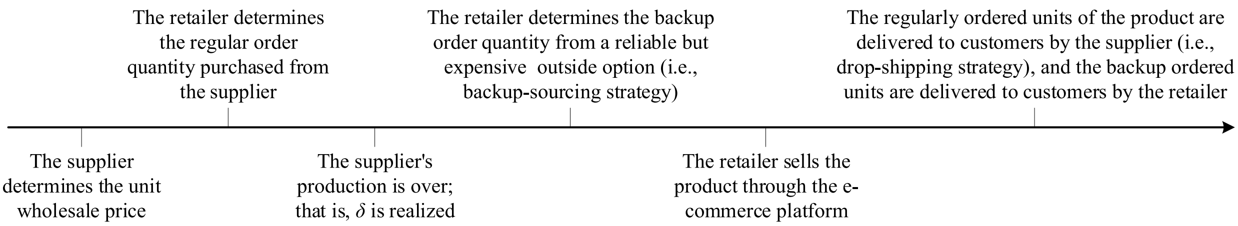

FIGURE 1. Timeline of the events.

In Scenario 2, the supplier and the retailer only exercise the drop-shipping strategy (see, subsection B). In Scenario 3, the retailer only exercises the backup-sourcing strategy (see, subsection C). In Scenario 4, both drop-shipping strategy and backup-sourcing strategy are activated (see, subsection D).

In order to distinguish the variables in different scenarios, subscripts 1, 2, 3, and 4 are used to represent the labels of Scenarios 1, 2, 3, and 4, respectively. For convenience, we refer to the retailer as "she" and the supplier as "he."

A. OPTIMAL DECISIONS WITHOUT THE DROP-SHIPPING STRATEGY AND BACKUP-SOURCING STRATEGY

In this subsection, we discuss the optimal decisions for the supplier and the retailer when neither the drop-shipping strategy nor the backup-sourcing strategy is activated (i.e., in Scenario 1). In this scenario, the retailer needs to determine the unit wholesale price, and the supplier needs to decide on the regular order quantity.

Through backward induction, we first analyze the decision of the retailer. Given the supplier's unit wholesale price w_1 (the subscript "1" is the label of Scenario 1), the retailer needs to determine the regular order quantity Q_{r1} to maximize her own expected profit π_1^R, i.e.,

$$\max_{Q_{r1}} \pi_1^R = aE_D[p\cdot\min(D, Q_{r1}) - w_1Q_{r1} - c_l\cdot\min(D, Q_{r1})] + (1-a)E_D[p\cdot\min(D, 0) - w_1\cdot 0 - c_l\cdot\min(D, 0)] \quad (1)$$

$$\text{s.t. } Q_{r1} \geq 0 \quad (2)$$

where the superscript R is the label of the retailer, $E_D[p\cdot\min(D, Q_{r1}) - w_1Q_{r1} - c_l\cdot\min(D, Q_{r1})]$ is the retailer's profit when $\delta = 1$ (i.e., no supply disruption occurs), and $E_D[p\cdot\min(D, 0) - w_1\cdot 0 - c_l\cdot\min(D, 0)]$ is that when $\delta = 0$ (supply disruption occurs).

Next, we analyze the wholesale price decision of the supplier. The supplier needs to determine the unit wholesale price w_1 to maximize his own expected profit π_1^M, i.e.,

$$\max_{w_1} \pi_1^M = aw_1Q_{r1} - cQ_{r1} - ac_lQ_{r1} \quad (3)$$

where aw_1Q_{r1} is the expected revenue of the supplier, cQ_{r1} is the supplier's production cost, and ac_lQ_{r1} is the expected logistics cost because the supplier has to deliver the product to the retailer.[3]

By solving the aforementioned two programs, Lemma 1 can be obtained.

Lemma 1: When neither the drop-shipping strategy nor the backup-sourcing strategy is activated (i.e., in Scenario 1), the optimal wholesale price decision of the supplier is

$$w_1^* = \frac{ap + c}{2a} \quad (4)$$

and the optimal regular order quantity decision of the supplier is

$$Q_{r1}^* = \frac{d(ap - 2ac_l - c)}{2a(p - c_l)} \quad (5)$$

According to Lemma 1, we have $\partial w_1^* / \partial a = -c/2a^2 < 0$ and $\partial Q_{r1}^* / \partial a = cd/2a^2(p - c_l) > 0$; that is, the wholesale price w_1^* of the supplier is decreasing in the reliability a, whereas the retailer's order quantity Q_{r1}^* is increasing in a. This is because the lower the reliability of the supplier, the higher the expected unit production cost. As a result, when the reliability of the supplier is low, he needs to set a high price to maintain his profit, and the order quantity of the retailer is decreased accordingly.

Combining equations (1), (3), (4) and (5), the optimal expected profit of the supplier in Scenario 1 is

$$\pi_1^{M*} = \frac{d}{4a(p - c_l)}(ap - 2ac_l - c)^2 \quad (6)$$

The corresponding optimal expected profit of the retailer is

$$\pi_1^{R*} = \frac{d}{8a(p - c_l)}(ap - 2ac_l - c)^2$$

[3] Note that the objective function of equation (3) is simplified from the following formula: $\pi_1^M = a(w_1 - c - c_l)Q_{r1} + (1-a)(w_1\cdot 0 - c_l\cdot 0 - cQ_{r1})$, which means that when the supply disruption occurs, the supplier's post-profit (i.e., $w_1\cdot 0 - c_l\cdot 0 - cQ_{r1}$) is negative. This setting is realistic, because in practice, the disruption risk often stems from a variety of emergencies, such as natural disasters, political unrest, terrorist attacks, worker strikes, etc. When such risk events (with small probability) occur, productive firms will inevitably encounter losses (i.e., negative profit). In addition, despite this, our mathematical program (i.e., equation (3)) can ensure that the supplier's (ex-ante) expected profit is positive, because the supplier's wholesale price decision is made before the randomness is realized. Furthermore, even if we consider the salvage value, it will not change any property of the results obtained in this paper, and the only difference is to replace c in the current results with $c - s$, where s is the unit salvage value. In fact, our setting that does not consider the salvage value is very common in the studies related to the risk of supply disruption (e.g., [3], [12], [17], [20], [35]–[37]).

B. OPTIMAL DECISIONS WITH ONLY DROP-SHIPPING STRATEGY

In this subsection, we discuss the optimal decisions for the supplier and the retailer when only the drop-shipping strategy is activated (i.e., in Scenario 2). In this scenario, the supplier needs to determine the wholesale price, and the retailer needs to decide on the regular order quantity.

Through backward induction, we first analyze the order decision of the retailer. Given the supplier's wholesale price w_2 (subscript 2 is the label of Scenario 2), the retailer needs to determine the order quantity Q_{r2} to maximize her own expected profit π_2^R, i.e.,

$$\max_{Q_{r2}} \pi_2^R = aE_D[p \cdot \min(D, Q_{r2}) - w_2 Q_{r2} - c_l \cdot \min(D, Q_{r2})] \quad (7)$$

$$\text{s.t. } Q_{r2} \geq 0$$

where $p \cdot \min(D, Q_{r2})$ is the revenue that the retailer obtains when $\delta = 1$, $w_2 Q_{r2}$ is the corresponding order cost of the retailer, and $c_l \cdot \min(D, Q_{r2})$ is the logistics cost paid to the supplier who directly delivers the product to customers according to the retailer's requirement.

Next, we analyze the decision of the supplier. The supplier only needs to determine a wholesale price w_2 to maximize his own expected profit, i.e.,

$$\max_{w_2} \pi_2^M = aw_2 Q_{r2} - cQ_{r2} \quad (8)$$

where $aw_2 Q_{r2}$ is the supplier's expected revenue and cQ_{r2} is his production cost.

To solve the aforementioned 2 programs, Lemma 2 can be obtained.

Lemma 2: When the retailer only exercises the drop-shipping strategy (i.e., in Scenario 2), the optimal wholesale price decision of the supplier is

$$w_2^* = \frac{ap + c - ac_l}{2a} \quad (9)$$

and the optimal regular order quantity decision of the retailer is

$$Q_{r2}^* = \frac{d(ap - ac_l - c)}{2a(p - c_l)} \quad (10)$$

According to Lemma 1 and 2, we can obtain Corollary 1.

Corollary 1: Compared with Scenario 1 (i.e., neither the drop-shipping strategy nor the backup-sourcing strategy is activated), the implementation of the drop-shipping strategy (i.e., Scenario 2) decreases the wholesale price of the supplier, i.e., $w_2^* < w_1^*$, but increases the regular order quantity of the retailer, i.e., $Q_{r2}^* > Q_{r1}^*$.

When the drop-shipping strategy is not activated (i.e., in Scenario 1), the cost of the supplier consists of two parts; that is, production cost and logistics cost. However, the usage of the drop-shipping strategy (i.e., Scenario 2) saves the logistics cost for the supplier; thus, the wholesale price of the supplier is reduced and the order quantity of the retailer is correspondingly increased. The management insight of Corollary 1 is that the implementation of drop-shipping improves the efficiency of the supply chain.

Combining equations (7), (8), (9) and (10), the optimal expected profit of the supplier in Scenario 2 is

$$\pi_2^{M*} = \frac{d}{4a(p - c_l)}(ap - ac_l - c)^2 \quad (11)$$

Correspondingly, the optimal expected profit of the retailer is

$$\pi_2^{R*} = \frac{d}{8a(p - c_l)}(ap - ac_l - c)^2$$

C. OPTIMAL DECISIONS WITH ONLY BACKUP-SOURCING STRATEGY

In this subsection, we discuss the optimal decisions for the supplier and the retailer when only the backup-sourcing strategy is activated (i.e., in Scenario 3). In this scenario, the supplier needs to determine the wholesale price, and the retailer needs to decide on both the regular order quantity and the backup order quantity.

Through backward induction, we first analyze the backup order decision of the retailer. Given the supplier's wholesale price w_3 (subscript 3 labels Scenario 3), the retailer's regular order quantity Q_{r3}, and the realized yield rate δ, the retailer needs to determine the backup order quantity Q_{b3} to maximize her profit π_{b3}^R; that is,

$$\begin{aligned} \max_{Q_{b3}} \pi_{b3}^R &= E_D[p \cdot \min(D, Q_{b3} + \delta Q_{r3}) - w_3 \delta Q_{r3} \\ &\quad - rQ_{b3} - c_l(\min(D, Q_{b3} + \delta Q_{r3}))] \quad (12) \\ \text{s.t. } & Q_{b3} \geq 0 \quad (13) \end{aligned}$$

where $p \cdot \min(D, Q_{b3} + \delta Q_{r3})$ is the retailer's revenue, $w_3 \delta Q_{r3}$ is the regular order cost, rQ_{b3} is the backup order cost, and $c_l(\min(D, Q_{b3} + \delta Q_{r3}))$ is the logistics cost yielded by delivering the product from the retailer side to customers.

Next, we analyze the retailer's regular order decision. Given the supplier's wholesale price w_3, the retailer needs to determine the regular order quantity Q_{r3} to maximize her own expected profit π_3^R, i.e.,

$$\begin{aligned} \max_{Q_{r3}} \pi_3^R &= aE_D[p \cdot \min(D, Q_{b3} + Q_{r3}) - w_3 Q_{r3} \\ &\quad - rQ_{b3} - c_l(\min(D, Q_{b3} + Q_{r3}))] \quad (14) \\ &\quad + (1 - a)E_D[p \cdot \min(D, Q_{b3}) - rQ_{b3} \\ &\quad - c_l(\min(D, Q_{b3}))] \\ \text{s.t. } & Q_{r3} \geq 0 \end{aligned}$$

where $E_D[p \cdot \min(D, Q_{b3} + Q_{r3}) - w_3 Q_{r3} - rQ_{b3} - c_l(\min(D, Q_{b3} + Q_{r3}))]$ is the profit of the retailer when $\delta = 1$, and $E_D[p \cdot \min(D, Q_{b3}) - rQ_{b3} - c_l(\min(D, Q_{b3}))]$ is the profit of the retailer when $\delta = 0$.

Finally, we analyze the supplier's wholesale price decision. The supplier only needs to determine the wholesale price w_3 to maximize his own expected profit π_3^M, i.e.,

$$\max_{w_3} \pi_3^M = aw_3 Q_{r3} - cQ_{r3} - ac_l Q_{r3} \quad (15)$$

where aw_3Q_{r3} is the supplier's expected revenue, cQ_{r3} is the supplier's production cost, and ac_lQ_{r3} is the expected logistics cost incurred by the supplier to deliver the product to the retailer.

To solve the aforementioned 3 programs, Lemma 3 can be obtained.

Lemma 3: When the retailer only exercises the backup-sourcing strategy (i.e., in Scenario 3), the optimal wholesale price of the supplier is

$$w_3^* = \begin{cases} (ap+c)/2a, & r \geq (ap+c)/2a \\ r, & r < (ap+c)/2a \end{cases}$$

the optimal regular order quantity of the retailer is

$$Q_{r3}^* = \begin{cases} d(ap-2ac_l-c)\big/2a(p-c_l), & r \geq (ap+c)\big/2a \\ d(p-c_l-r)\big/(p-c_l), & r < (ap+c)\big/2a \end{cases}$$

and the optimal backup order quantity of the retailer is

$$Q_{b3}^* = \begin{cases} 0, & \delta = 1 \\ d(p-c_l-r)\big/(p-c_l), & \delta = 0 \end{cases}$$

Lemma 3 shows that in Scenario 3 (i.e., when only the backup-sourcing strategy is activated), the retailer orders from the supplier even if the wholesale price of the supplier equals to the backup-sourcing cost, i.e., $w_3^* = r$. This is because, in this case, there is no difference between regular ordering and backup-sourcing for the retailer in terms of the profit. However, in order to maintain a long-term relationship with the supplier, the retailer tends to order from the supplier. Moreover, even if the regular order is not eventually delivered (i.e., a supply disruption occurs), the retailer can still implement backup-sourcing at a unit cost of r.

Corollary 2: Compared with Scenario 1 (i.e., neither the drop-shipping strategy nor the backup-sourcing strategy is activated), the implementation of the backup-sourcing strategy (i.e., Scenario 3) reduces the wholesale price of the supplier, i.e., $w_3^* \leq w_1^*$, but increases the regular order quantity of the retailer, i.e., $Q_{r3}^* \geq Q_{r1}^*$.

As we all know, the backup-sourcing strategy plays a significant role in mitigating supply risk. Interestingly, however, Corollary 2 indicates that the backup-sourcing strategy also plays a role in reducing the wholesale price of the upstream firm. This is because the unit cost of the backup order is r, which forces the wholesale price of the supplier not to be higher than r, otherwise the retailer will give up the regular ordering and directly implement the backup-sourcing. Thus, the usage of the backup-sourcing strategy is equivalent to introducing a competitor to the supplier. Then the supplier has to lower his wholesale price, and the retailer accordingly increases the regular order quantity.

Combining (14), (15) and Lemma 3, we obtain the optimal expected profit of the supplier in Scenario 3 as follows

$$\pi_3^{M*} = \begin{cases} \dfrac{d(ap-2ac_l-c)^2}{4a(p-c_l)}, & r \geq \dfrac{ap+c}{2a} \\ \dfrac{d(p-c_l-r)(ar-ac_l-c)}{(p-c_l)}, & r < \dfrac{ap+c}{2a} \end{cases} \quad (16)$$

and corresponding optimal expected profit of the retailer as follows

$$\pi_3^{R*} = \begin{cases} \dfrac{d(ap-2ac_l-c)^2}{(8a(p-c_l))} + \dfrac{(1-a)d(p-c_l-r)^2}{2(p-c_l)}, & r \geq \dfrac{ap+c}{2a} \\ \dfrac{d(p-c_l-r)^2}{(2(p-c_l))}, & r < \dfrac{ap+c}{2a} \end{cases}$$

D. OPTIMAL DECISIONS WITH BOTH DROP-SHIPPING STRATEGY AND BACKUP-SOURCING STRATEGY

In this subsection, we discuss the optimal decisions for the supplier and the retailer when both the drop-shipping strategy and the backup-sourcing strategy are activated (i.e., in Scenario 4). In this scenario, the supplier needs to determine the wholesale price, and the retailer needs to decide on both the regular order quantity and the backup order quantity.

Through backward induction, we first analyze the backup order decision of the retailer. Given the wholesale price w_4 of the supplier (subscript 4 is the label of Scenario 4), the regular order quantity Q_{r4} of the retailer, and the realized yield rate δ, the retailer needs to determine the backup order quantity Q_{b4} to maximize her profit π_{b4}^R, i.e.,

$$\begin{aligned} \max_{Q_{b4}} \ \pi_{b4}^R &= E_D[p \cdot \min(D, Q_{b4} + \delta Q_{r4}) - w_4\delta Q_{r4} \\ &\quad - rQ_{b4} - c_l(\min(D, Q_{b4} + \delta Q_{r4}))] \quad (17) \\ \text{s.t. } & Q_{b4} \geq 0 \quad (18) \end{aligned}$$

where $p \cdot \min(D, Q_{b4} + \delta Q_{r4})$ is the retailer's revenue, $w_4\delta Q_{r4}$ is the regular order cost, rQ_{b4} is the backup order cost, and $c_l(\min(D, Q_{b4} + \delta Q_{r4}))$ is the total logistics cost.

Next, we analyze the regular order decision of the retailer. Given the supplier's wholesale price w_4, the retailer needs to determine the regular order quantity Q_{r4} to maximize her own expected profit π_4^R, i.e.,

$$\begin{aligned} \max_{Q_{r4}} \ \pi_4^R &= aE_D[p \cdot \min(D, Q_{b4} + Q_{r4}) - w_4Q_{r4} - rQ_{b4} - c_l \\ &\quad \cdot (\min(D, Q_{b4} + Q_{r4}))] + (1-a)E_D[p \\ &\quad \cdot \min(D, Q_{b4}) - rQ_{b4} - c_l(\min(D, Q_{b4}))] \\ \text{s.t. } & Q_{r4} \geq 0 \quad (19) \end{aligned}$$

where $E_D[p \cdot \min(D, Q_{b4} + Q_{r4}) - w_4Q_{r4} - rQ_{b4} - c_l(\min(D, Q_{b4} + Q_{r4}))]$ is the retailer's profit when $\delta = 1$, and $E_D[p \cdot \min(D, Q_{b4}) - rQ_{b4} - c_l(\min(D, Q_{b4}))]$ is the retailer's profit when $\delta = 0$.

Finally, we analyze the wholesale price decision of the supplier. The supplier only needs to determine the unit wholesale price w_4 to maximize his own expected profit, i.e.,

$$\max_{w_4} \ \pi_4^M = aw_4Q_{r4} - cQ_{r4} \quad (20)$$

where aw_4Q_{r4} is the supplier's expected revenue and cQ_{r4} is his production cost.

To solve the aforementioned 3 programs, Lemma 4 can be obtained.

Lemma 4: When both the drop-shipping strategy and the backup-sourcing strategy are activated (i.e., in Scenario 4), the optimal wholesale price of the supplier is

$$w_4^* = \begin{cases} (ap + c - ac_l)/2a, & r \geq (ap + c - ac_l)/2a \\ r, & r < (ap + c - ac_l)/2a \end{cases}$$

the optimal regular order quantity of the retailer is

$$Q_{r4}^* = \begin{cases} d(ap - ac_l - c)\big/(2a(p - c_l)), & r \geq (ap + c - ac_l)\big/2a \\ d(p - c_l - r)\big/(p - c_l), & r < (ap + c - ac_l)\big/2a \end{cases}$$

and the optimal backup order quantity of the retailer is

$$Q_{b4}^* = \begin{cases} 0, & \delta = 1 \\ d(p - c_l - r)\big/(p - c_l), & \delta = 0 \end{cases}$$

Corollary 3: Compared with Scenario 3 (Scenario 2), the implementation of drop-shipping strategy (backup-sourcing strategy) reduces the wholesale price of the supplier, i.e., $w_4^* \leq w_3^*$ ($w_4^* \leq w_2^*$), but increases the regular order quantity of the retailer, i.e., $Q_{r4}^* \geq Q_{r3}^*$ ($Q_{r4}^* \geq Q_{r2}^*$).

Recall that Corollaries 1 and 2 show that the implementation of drop-shipping or backup-sourcing reduces the wholesale price of the supplier. Interestingly, Corollary 3 indicates that the joint use of the two strategies further reduces the supplier's wholesale price. This is because, as mentioned before, the usage of the drop-shipping strategy can reduce the cost of the supplier, and the usage of the backup-sourcing strategy is equivalent to introducing a competitor to the supplier; that is, both the two strategies have the effect on reducing the wholesale price of the supplier. Thus, the wholesale price when both the two strategies are activated is lower than that when only one strategy is used. Furthermore, the reduction of the wholesale price naturally leads to an increase in the regular order quantity of the retailer.

Combining (19), (20) and Lemma 4, the optimal expected profit of the supplier in Scenario 4 is as follows: (1) if $c_l < (ap - c)\big/3a$, then

$$\pi_4^{M^*} = \begin{cases} \dfrac{d(ap - ac_l - c)^2}{4a(p - c_l)}, & r \geq \dfrac{ap + c - ac_l}{2a} \\ \dfrac{d(p - r - c_l)(ar - c)}{p - c_l}, & r < \dfrac{ap + c - ac_l}{2a} \end{cases} \tag{21}$$

(2) If $c_l \geq (ap - c)\big/3a$, then

$$\pi_4^{M^*} = d(ap - ac_l - c)^2/4a(p - c_l) \tag{22}$$

Similarly, the optimal expected profit of the retailer in Scenario 4 is

$$\pi_4^{R*} = \max\left[\frac{d(ap - ac_l - c)^2}{8a(p - c_l)} + \frac{(1 - a)d(p - c_l - r)^2}{2(p - c_l)}, \frac{d(p - c_l - r)^2}{2(p - c_l)}\right]$$

V. VALUES OF THE DROP-SHIPPING STRATEGY AND BACKUP-SOURCING STRATEGY

In this section, we will discuss the impacts of drop-shipping strategy and backup-sourcing strategy on the profits of the supplier, the retailer and the supply chain.

Proposition 1: Regardless of whether backup-sourcing (drop-shipping) strategy is activated, the implementation of drop-shipping (backup-sourcing) strategy can increase the profit of the retailer, i.e., $\pi_2^{R*} > \pi_1^{R*}$ and $\pi_4^{R*} \geq \pi_3^{R*}$ ($\pi_3^{R*} > \pi_1^{R*}$ and $\pi_4^{R*} > \pi_2^{R*}$).

Proposition 1 shows that when the backup-sourcing strategy is not activated (i.e., in Scenarios 1 and 2), the implementation of drop-shipping strategy increases the retailer's profit, i.e., $\pi_2^{R*} > \pi_1^{R*}$. Similarly, when the backup-sourcing strategy is activated (i.e., in Scenarios 3 and 4), the usage of drop-shipping strategy also increases the retailer's profit, i.e., $\pi_4^{R*} \geq \pi_3^{R*}$. This is because the usage of drop-shipping strategy can reduce the cost of the supplier, thereby reducing his wholesale price. Correspondingly, the order quantity of the retailer increases; as a result, the retailer's profit increases, too. Proposition 1 also shows that when the drop-shipping strategy is not activated (Scenarios 1 and 3), the implementation of the backup-sourcing strategy increases the retailer's profit, i.e., $\pi_3^{R*} > \pi_1^{R*}$. Similarly, the usage of the backup-sourcing strategy also increases the retailer's profit, i.e., $\pi_4^{R*} > \pi_2^{R*}$, when activating the drop-shipping strategy (Scenarios 2 and 4). This is because the backup-sourcing strategy can mitigate the supply disruption risk.

Define

$$V_d^R = \pi_2^{R*} - \pi_1^{R*}$$

as the value of drop-shipping strategy to the retailer when the backup-sourcing strategy is not activated. Similarly, define

$$V_{bd}^R = \pi_4^{R*} - \pi_3^{R*}$$

as the value of drop-shipping to the retailer when the backup-sourcing strategy is activated. Define

$$V_b^R = \pi_3^{R*} - \pi_1^{R*}$$

as the value of backup-sourcing strategy to the retailer when the drop-shipping strategy is not activated. Similarly, define

$$V_{db}^R = \pi_4^{R*} - \pi_2^{R*}$$

as the value of the backup-sourcing strategy to the retailer when the drop-shipping strategy is activated. Then we have Proposition 2.

Proposition 2: For the retailer, there is substitutability between the drop-shipping and backup-sourcing strategies, i.e., $V_{bd}^R \leq V_d^R$ and $V_{db}^R \leq V_b^R$.

Interestingly, Proposition 2 shows that the two seemingly unrelated strategies of drop-shipping and backup-sourcing are substitutive. This is because for one thing, from the aforementioned analysis (i.e., Corollary 1), it can be found that the usage of the drop-shipping strategy can decrease the wholesale price of the supplier. Thus, the retailer increases the regular order quantity; that is, the drop-shipping strategy

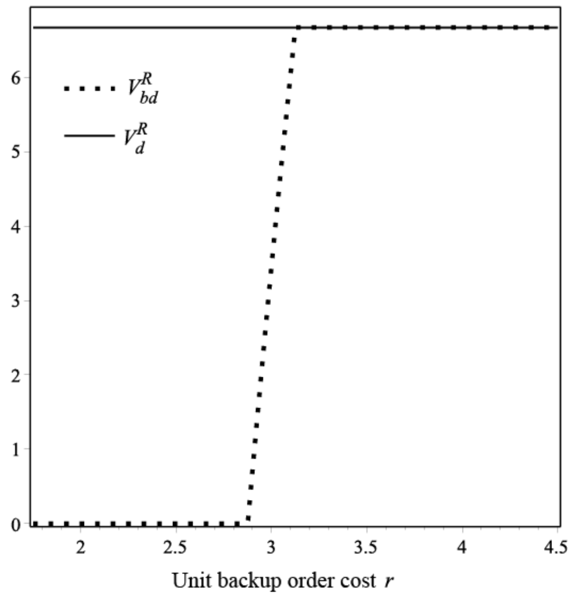

FIGURE 2. Substitutability between the drop-shipping and backup-sourcing strategies for the retailer.

Note: V_{bd}^R (V_d^R) is the value of drop-shipping strategy to the retailer when the backup-sourcing strategy is (not) activated; the parameters are $d = 100, c = 1, p = 5, c_l = 0.5, a = 0.8$.

makes the retailer more dependent on the supplier. At this time, if the backup-sourcing strategy is added, which is equivalent to introducing a competitor to the supplier, the retailer's regular order quantity will decrease; that is, the dependence of the retailer on the supplier will be reduced. Therefore, the implementation of the backup-sourcing strategy reduces the value of drop-shipping (i.e., $V_{bd}^R \leq V_d^R$). For another, the usage of backup-sourcing strategy can mitigate supply risk. At this time, if the drop-shipping strategy is added, the wholesale price of the supplier will decrease (see, Corollary 1), and the retailer's regular order quantity will increase; that is, the retailer is less dependent on the backup-sourcing. Thus, the implementation of the drop-shipping strategy also reduces the value of the backup-sourcing strategy (i.e., $V_{db}^R \leq V_b^R$). Based on the aforementioned two aspects, there is substitutability between the two strategies. The management insight is that when both the two strategies are activated, the benefits that the retailer receives are less than expected. In other words, for the retailer, the drop-shipping and backup-sourcing may not be the most ideal strategic combination. Thus, the retailer can try other risk-mitigating or cost-saving strategies to find out a better combination of strategies.

Figure 2 visualizes the formula $V_{bd}^R \leq V_d^R$, which is equivalent to $V_{db}^R \leq V_b^R$ according to the proof of Proposition 2; that is, this figure illustrates the results of Proposition 2. In addition, it can be also found from Figure 2 that in the case of activating the backup-sourcing strategy, the value of drop-shipping strategy to the retailer (i.e., V_{bd}^R) is equal to zero when r is small, increasing when r is moderate, and constant when r is large. This is because when r is small, the supplier's wholesale price is equal to the unit backup order cost r (see, Lemma 4). It means that there is no difference between regular ordering and backup-sourcing; thus, the value of drop-shipping strategy to the retailer is zero. When r is moderate, the wholesale price of the supplier is less than the unit backup order cost r, and the retailer has the cost advantage through regular ordering, so the value of drop-shipping strategy to the retailer is positive; moreover, with the increasing of the unit backup order cost r, the retailer decreases the backup order quantity and correspondingly increases the regular order quantity, then the value of drop-shipping strategy to the retailer also increases. When r is large, the retailer only places regular order without backup-sourcing; thus, the value of drop-shipping strategy to the retailer reaches the maximum and remains constant. Figure 2 also shows that $V_d^R - V_{bd}^R$ weakly decreases in r; that is, for the retailer, the substitutability of the two strategies decreases in the backup-sourcing cost. This is because, with the unit backup-sourcing cost increasing, the backup order quantity decreases. As a result, the substitutability of the two strategies is weakened.

There is rich literature that investigates drop-shipping (e.g., [4], [6], [7], [9], [11], [33]) or backup-sourcing (e.g., [12], [14], [15], [17], [18], [20], [21]) strategy. These studies show that the use of drop-shipping or backup-sourcing strategy can increase the downstream retailer's profit. Different from the existing research, our study considers both of the two strategies, and finds that although each strategy can increase the retailer's profit, there is substitutability between the two strategies for the retailer; that is, when both of the two strategies are activated, the retailer's profit increment will be less than expected. Furthermore, our study also shows that such substitutability decreases in the backup-sourcing cost.

Proposition 3: The implementation of the drop-shipping strategy increases the supplier's profit, i.e., $\pi_2^{M*} > \pi_1^{M*}$ and $\pi_4^{M*} > \pi_3^{M*}$; whereas the usage of the backup-sourcing strategy decreases the supplier's profit, i.e., $\pi_3^{M*} \leq \pi_1^{M*}$ and $\pi_4^{M*} \leq \pi_2^{M*}$.

Proposition 3 shows that no matter whether the backup-sourcing strategy is activated (Scenarios 3 and 4) or not (Scenarios 1 and 2), the implementation of drop-shipping increases the supplier's profit, i.e., $\pi_2^{M*} > \pi_1^{M*}$ and $\pi_4^{M*} > \pi_3^{M*}$. This is because the usage of drop-shipping strategy can reduce the cost of the supplier (i.e., save the logistics cost for the supplier). Proposition 3 also shows that no matter whether the drop-shipping strategy is activated (Scenarios 2 and 4) or not (Scenarios 1 and 3), the implementation of the backup-sourcing strategy reduces the supplier's profit, i.e., $\pi_3^{M*} \leq \pi_1^{M*}$ and $\pi_4^{M*} \leq \pi_2^{M*}$. This is because the implementation of the backup-sourcing strategy is equivalent to introducing a competitor to the supplier, forcing the supplier to lower his wholesale price (Corollary 3.2); as a result, the supplier's profit is reduced.

Define

$$V_d^M = \pi_2^{M*} - \pi_1^{M*}$$

as the value of the drop-shipping strategy to the supplier when the backup-sourcing strategy is not activated. Similarly, define

$$V_{bd}^M = \pi_4^{M*} - \pi_3^{M*}$$

as the value of the drop-shipping strategy to the supplier when the backup-sourcing strategy is activated. Define

$$V_b^M = \pi_3^{M*} - \pi_1^{M*}$$

as the (negative) value of backup-sourcing strategy to the supplier when the drop-shipping strategy is not activated. Note that V_b^M is negative; thus, V_b^M is actually a loss to the supplier caused by the retailer implementing backup-sourcing strategy. Similarly, define

$$V_{db}^M = \pi_4^{M*} - \pi_2^{M*}$$

as the (negative) value of the backup-sourcing strategy to the supplier when the drop-shipping strategy is activated. Then we obtain Proposition 4.

Proposition 4: For the supplier, the drop-shipping and backup-sourcing are complementary strategies, i.e., $V_{bd}^M \geq V_d^M$ and $V_{db}^M \geq V_b^M$.

For the supplier, the implementation of the backup-sourcing strategy reduces his profit (Proposition 3); thus, it would be intuitive to imagine that the usage of the backup-sourcing strategy also reduces the value of the drop-shipping strategy. However, according to Proposition 4, the fact is exactly the opposite: the implementation of the backup-sourcing strategy increases the value of the drop-shipping strategy; i.e., $V_{bd}^M \geq V_d^M$. This is because the backup-sourcing strategy is equivalent to introducing a competitor to the supplier, and then the supplier needs to use the drop-shipping strategy to reduce his cost to gain competitive advantage. As a result, the implementation of the backup-sourcing strategy increases the value of the drop-shipping strategy; that is, for the supplier, they are complementary strategies. The management insights are that although the backup-sourcing strategy results in the loss of the supplier's profit, this loss is smaller than expected when both the drop-shipping and backup-sourcing strategies are activated. Furthermore, according to the definitions of V_b^M, V_d^M, V_{db}^M and V_{bd}^M, it is not difficult to find that $\partial(V_{db}^M - V_b^M)/\partial c \geq 0$ and $\partial(V_{bd}^M - V_d^M)/\partial c \geq 0$; that is, the supplier can increase the complementary of the two strategies by reducing his production cost.

Figure 3 visualizes the result of Proposition 4 (i.e., $V_{bd}^M \geq V_d^M$). In addition, it can be also found from Figure 3 that when the backup-sourcing strategy is activated, the value of the drop-shipping strategy to the supplier (i.e., V_{bd}^M) fist decreases and then increases in r. This is because when r is low, the supplier sets a wholesale price which is exactly equal to the unit backup-sourcing cost r, i.e., $w_4^* = r$ (see, Lemma 4); then with the increase of r, the wholesale price increases, and the regular order quantity of the retailer decreases, thus, the value of the drop-shipping strategy to the supplier decreases. When r is large, the wholesale price of the supplier is less than the unit backup-sourcing cost (see, Lemma 4); then with the increase of r, the retailer reduces the backup-sourcing quantity and correspondingly increases the regular order quantity, thus, the value of the drop-shipping to the supplier increases. Figure 3 also shows that $V_{bd}^M - V_d^M$ first decreases and then increases in r, which means that for the supplier, the complementarity of the two strategies first decreases and then increases in r.

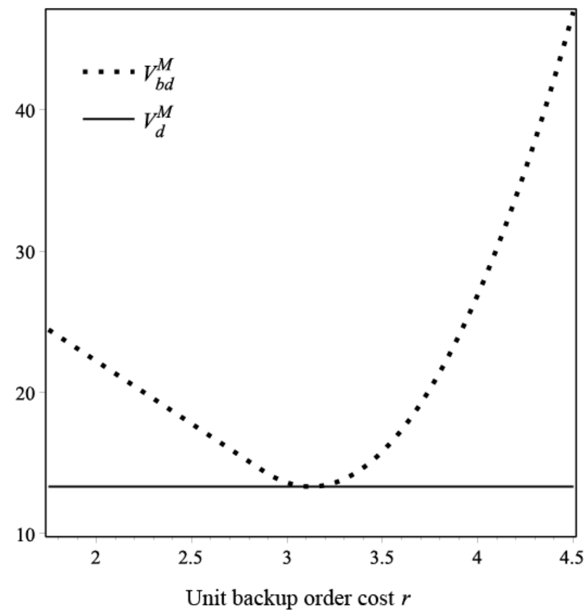

FIGURE 3. Complementarity between the drop-shipping and backup-sourcing strategies for the supplier.

Note: V_{bd}^M (V_d^M) is the value of drop-shipping strategy to the supplier when the backup-sourcing strategy is (not) activated; the parameters are $d = 100$, $c = 1$, $p = 5$, $c_l = 0.5$, $a = 0.8$.

To the best of our knowledge, there is abundant literature examining drop-shipping (e.g., [4], [6], [7], [9], [11], [33]) or backup-sourcing (e.g., [12], [14], [15], [17], [18], [20], [21]) strategy, which shows that the drop-shipping (backup-sourcing) strategy increases (decreases) the supplier's profit. Different from previous research, in this study, we consider both of the two strategies, and find that although the drop-shipping (backup-sourcing) strategy makes the supplier's profit increase (decrease), the implementation of backup-sourcing increases the value of the drop-shipping strategy for the supplier. Furthermore, such increment in value first decreases and then increases in the backup-sourcing cost.

Define

$$V_d^S = \pi_2^{R*} + \pi_2^{M*} - (\pi_1^{R*} + \pi_1^{M*})$$

as the value of drop-shipping strategy to the supply chain when the backup-sourcing strategy is not activated. Similarly, define

$$V_{bd}^S = \pi_4^{R*} + \pi_4^{M*} - (\pi_3^{R*} + \pi_3^{M*})$$

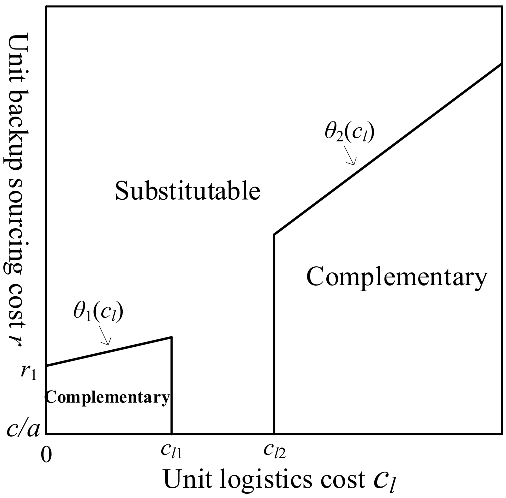

FIGURE 4. The relation between the drop-shipping and backup-sourcing strategies for the supply chain.

Note: $c_{l1} = 2(ap-c)/(7a)$; $c_{l2} = (ap-c)/(2a)$; $r_1 = (2ap+6c)/(8a)$; $\theta_1(c_l) = (ac_l+2ap+6c)/(8a)$, where $c_l < c_{l1}$; $\theta_2(c_l) = (4ac_l-ap+3c)/(8a)$, where $c_l \geq c_{l2}$.

as the value of drop-shipping strategy to the supply chain when the backup-sourcing strategy is activated. Define

$$V_b^S = \pi_3^{R*} + \pi_3^{M^*} - (\pi_1^{R*} + \pi_1^{M^*})$$

as the value of backup-sourcing strategy to the supply chain when the drop-shipping strategy is not activated. Similarly, define

$$V_{db}^S = \pi_4^{R*} + \pi_4^{M^*} - (\pi_2^{R*} + \pi_2^{M^*})$$

as the value of the backup-sourcing strategy to the supply chain when the drop-shipping strategy is activated. Then Proposition 5 is obtained.

Proposition 5: For the supply chain: *(i)* when $c_l \geq (ap-c)/(2a)$, the drop-shipping and backup-sourcing are either substitutive strategies (i.e., $V_{db}^S \leq V_b^S$, $V_{bd}^S \leq V_d^S$) if $r \geq (4ac_l - ap + 3c)\big/(2a)$, or complementary strategies (i.e., $V_{db}^S > V_b^S$, $V_{bd}^S > V_d^S$) if $r < (4ac_l - ap + 3c)\big/(2a)$; *(ii)* when $2(ap-c)\big/(7a) \leq c_l < (ap-c)\big/(2a)$, there is substitutability between the two strategies (i.e., $V_{db}^S \leq V_b^S$, $V_{bd}^S \leq V_d^S$); *(iii)* when $c_l < 2(ap-c)\big/(7a)$, the drop-shipping and backup-sourcing are either substitutive strategies (i.e., $V_{db}^S \leq V_b^S$, $V_{bd}^S \leq V_d^S$) if $r \geq (ac_l + 2ap + 6c)\big/(8a)$, or complementary strategies (i.e., $V_{db}^S > V_b^S$, $V_{bd}^S > V_d^S$) if $r < (ac_l + 2ap + 6c)\big/(8a)$.

Figure 4 visualizes the results of Proposition 5; that is, for the supply chain, there is either substitutability or complementarity between the drop-shipping and backup-sourcing strategies. This is because, for the retailer, there is substitutability of the two strategies (see, Proposition 2), whereas for the supplier, the two strategies are complementary (see, Proposition 4); thus, for the supply chain, the relationship of the two strategies depends on the trade-off between the substitutability and complementarity. Specifically, the low backup-sourcing cost is equivalent to introducing a strong competitor to the supplier, and the supplier urgently needs to reduce his own cost by drop-shipping to maintain his competitive advantage; that is, the backup-sourcing strategy has a significant role in enhancing the value of drop-shipping strategy, and the two strategies are significantly complementary to the supplier. Moreover, the high logistics cost makes the effect of the drop-shipping strategy on the reduction of the supplier's cost more significant; that is, the complementarity becomes stronger. Thus, when the logistics cost is high and the backup-sourcing cost is low (i.e., the lower right corner of Figure 4), the complementarity of the two strategies for the supplier dominate the substitutability of that for the retailer; that is, the two strategies are complementary for the supply chain. According to the aforementioned analysis, it can be found that the two strategies are complementary in the condition of low backup-sourcing cost. The low logistics cost makes the value of the drop-shipping strategy to the retailer small, thus, for the retailer, the existence of the backup-sourcing strategy weakens the value of the drop-shipping strategy; that is, the substitutability of the two strategies for the retailer is weak. As a result, when both the logistics cost and the backup-sourcing cost are low (i.e., the lower left corner of Figure 4), the complementarity of the two strategies for the supplier dominate the substitutability of that for the retailer; that is, the two strategies are complementary for the supply chain. In other cases, (i.e., in addition to the aforementioned two cases), according to similar analysis, it is easy to conclude that the substitutability of the two strategies for the retailer dominate the complementarity of that for the supplier; that is, the two strategies are substitutive for the supply chain.

The management insights of Proposition 5 are as follows. When the logistics cost is low or high and the backup-sourcing cost is low, both the drop-shipping and backup-sourcing strategies should be activated, because the supply chain can obtain higher-than-expected profit; whereas in other cases, the supply chain obtains lower-than-expected profit, thus, the supply chain can try other risk-mitigating or cost-saving strategies to find out the most ideal strategic combination.

Different from the existing studies which investigate drop-shipping (e.g., [4], [6], [7], [9], [11], [33]) or backup-sourcing (e.g., [12], [14], [15], [17], [18], [20], [21]) strategy separately, our study is the first to analyze the relationship between the two strategies. Furthermore, we show that for the supply chain, the drop-shipping and backup-sourcing are either substitutive strategies when the logistics cost is low or high and the backup-sourcing cost is low, or complementary strategies when the opposite is the case.

VI. EXTENSION

In this section, we extend our model to the situation where demand D follows the general distribution with cumulative distribution function F and probability density function f on $[0, d]$ (e.g., [39]). Then we obtain Lemma 5.

Lemma 5: When demand D follows the general distribution, in the Scenario of both drop-shipping and backup-sourcing strategies being activated, the optimal wholesale price of the supplier is

$$w_4^{E*} = \min(r, w^*)$$

the optimal regular order quantity of the retailer is

$$Q_{r4}^* = F^{-1}(1 - \frac{\min(r, w^*)}{p - c_l})$$

and the optimal backup order quantity of the retailer is

$$Q_{b4}^* = \begin{cases} F^{-1}(1 - \dfrac{r}{p - c_l}), & \delta = 0 \\ 0, & \delta = 1 \end{cases}$$

where

$$w^* = \arg\max\ (aw - c)F^{-1}[1 - \frac{w}{p - c_l}].$$

Lemma 5 extends the results of Lemma 4. Similarly, the optimal decisions of the retailer and the supplier in other simpler scenarios (i.e., Lemmas 1, 2, and 3) can also be extended to the situation where demand D follows the general distribution, and the idea of the extensions is similar to Lemma 5. For simplicity, we don't repeat them here.

VII. CONCLUSION

Considering the supply disruption risk, we investigate the optimal order decisions of the e-retailer and the optimal wholesale price decision of the supplier when the drop-shipping strategy and the backup-sourcing strategy can be activated. The relationship of the two strategies is also examined in this paper.

We find that the implementation of drop-shipping strategy reduces the wholesale price of the supplier and increases the regular order quantity of the retailer, as does the implementation of backup-sourcing strategy. For the retailer, both the drop-shipping and backup-sourcing strategies can increase her profit, and there is substitutability between the two strategies. This is because drop-shipping strategy makes the wholesale price of the supplier decrease and the regular order quantity of the retailer increase; that is, it makes the retailer less dependent on the backup-sourcing. Thus, for the retailer, the implementation of drop-shipping strategy reduces the value of the backup-sourcing strategy (i.e., the two strategies are substitutive). We also observe that for the supplier, the drop-shipping strategy makes his profit increase, whereas the backup-sourcing strategy makes that decrease; but the drop-shipping and backup-sourcing are complementary strategies for him. This is because the backup-sourcing strategy is equivalent to introducing a competitor to the supplier, and then the supplier needs to use drop-shipping strategy to reduce his cost to gain competitive advantage. As a result, for the supplier, the implementation of the backup-sourcing strategy increases the value of the drop-shipping strategy (i.e., the two strategies are complementary). Furthermore, depends on the trade-off between the substitutability of the two strategies for the retailer and the complementarity of that for the supplier, for the supply chain, the drop-shipping and backup-sourcing are either substitutive strategies when the logistics cost is low or high and the backup-sourcing cost is low, or complementary strategies when the opposite is the case. Finally, by numerical study, we show that for the retailer, the substitutability of the two strategies decreases in the backup-sourcing cost, and for the supplier, the complementarity between the two strategies first decreases and then increases in the backup-sourcing cost.

There are several extension directions for this paper. First, our study assumes that the production cost is linear; but in reality, there may be economies or diseconomies of scale for production. Thus, this paper can be extended to the situation of nonlinear production cost. In this situation, it is an interesting research question how the economies/diseconomies of scale will affect the substitutability or complementarity between the drop-shipping and backup-sourcing strategies. Second, we assume that the supplier's unit production cost is common knowledge in this paper; however, in operational practice, the unit production cost may be the supplier's private information, so the future research can extend this study to the case of asymmetric information. In this case, it is difficult but significant to investigate how the existence of asymmetric information affect the role of backup-sourcing strategy in risk mitigating, the value of drop-shipping strategy in cost saving, and the substitutability or complementarity between the above two strategies.

APPENDIX

Proof of Lemma 1: To solve (1), two cases are discussed as follows.

(1) If $Q_{r1} \le d$, then

$$\min(D, Q_{r1}) = \begin{cases} D, & D \le Q_{r1} \\ Q_{r1}, & D > Q_{r1} \end{cases}$$

Thus,

$$\begin{aligned}
\pi_1^R &= a(p - c_l)\int_0^d \frac{\min(D, Q_{r1})}{d} dD - aw_1 Q_{r1} \\
&= a(p - c_l)\left[\int_0^{Q_{r1}} \frac{\min(D, Q_{r1})}{d} dD + \int_{Q_{r1}}^d \frac{\min(D, Q_{r1})}{d} dD\right] \\
&\quad - aw_1 Q_{r1} \\
&= a(p - c_l)\left[\int_0^{Q_{r1}} \frac{D}{d} dD + \int_{Q_{r1}}^d \frac{Q_{r1}}{d} dD\right] - aw_1 Q_{r1} \\
&= -\frac{a(p - c_l)Q_{r1}^2}{2d} + a(p - c_l - w_1)Q_{r1}
\end{aligned}$$

(2) If $Q_{r1} > d$, then $\min(D, Q_{r1}) = D$. Thus,

$$\pi_1^R = a(p - c_l)\int_0^d \frac{D}{d} dD - aw_1 Q_{r1} = -aw_1 Q_{r1} + \frac{1}{2}a(p - c_l)d$$

As a result,

$$\pi_1^R(Q_{r1}) = \begin{cases} -\dfrac{a(p - c_l)}{2d} Q_{r1}^2 + a(p - c_l - w_1)Q_{r1}, & Q_{r1} \le d \\ -aw_1 Q_{r1} + \dfrac{a(p - c_l)d}{2}, & Q_{r1} > d \end{cases}$$

It is not difficult to find that the aforementioned piecewise function is continuous. Furthermore, the first segment of the piecewise function is concave and its FOC (the first-order-condition) solution is $Q_{r1} = d(p - w_1 - c_l)/(p - c_l)$. The second segment of the piecewise function is decreasing in Q_{r1}. Since $d(p - w_1 - c_l)/(p - c_l) < d$, $\pi_1^R(Q_{r1})$ can reach the maximum value at $Q_{r1} = d(p - w_1 - c_l)/(p - c_l)$. Combining with the constraint condition (2), we have

$$Q_{r1}^* = \max\left(\frac{d(p - w_1 - c_l)}{p - c_l}, 0\right) \tag{A1}$$

Substituting equation (A1) into (3), we obtain

$$\pi_1^M(w_1) = \begin{cases} \dfrac{d(w_1+c_l-p)(c+ac_l-aw_1)}{p-c_l}, & w_1 < p-c_l \\ 0, & w_1 \ge p-c_l \end{cases}$$

The first segment of the above function is concave and its FOC solution is $w_1 = (ap + c)/2a$. According to Assumptions 1 and 2, it is not difficult to find that $(ap + c)/2a < p - c_l$; thus, the optimal solution of $\pi_1^M(w_1)$ is $w_1^* = (ap + c)/2a$. Then substituting w_1^* into (A1) results in equation (5). □

Proof of Lemma 2: Following the same argument of the proof of Lemma 1, Lemma 2 is obtained. □

Proof of Corollary 1: According to Lemmas 1 and 2, we have $w_2^* - w_1^* = -c_l/2$ and $Q_{r2}^* - Q_{r1}^* = c_l d/(2p - 2c_l)$. Therefore, $w_2^* < w_1^*$, and $Q_{r2}^* > Q_{r1}^*$. □

Proof of Lemma 3: We first solve the program (12). Since the realized δ is either equal to 0, or equal to 1, two cases are discussed as follows.

(1) When $\delta = 0$, the objective function of (12) can be rewritten as

$$\begin{aligned} \pi_{b3}^R &= (p - c_l)\int_0^d \frac{\min(D, Q_{b3})}{d}dD - rQ_{b3} \\ &= (p - c_l)\left[\int_0^{Q_{b3}} \frac{\min(D, Q_{b3})}{d}dD \right. \\ &\quad \left. + \int_{Q_{b3}}^d \frac{\min(D, Q_{b3})}{d}dD\right] - rQ_{b3} \\ &= (p - c_l)\left[\int_0^{Q_{b3}} \frac{D}{d}dD + \int_{Q_{b3}}^d \frac{Q_{b3}}{d}dD\right] - rQ_{b3} \\ &= -\frac{p - c_l}{2d}Q_{b3}^2 + (p - c_l - r)Q_{b3} \end{aligned}$$

Obviously, the aforementioned function is concave on Q_{b3} and its FOC solution is $Q_{b3} = d(p - c_l - r)/(p - c_l) > 0$, which is the optimal solution in the case of $\delta = 0$.

(2) When $\delta = 1$, the objective function of (12) can be similarly rewritten as

$$\begin{aligned} \pi_{b3}^R = \frac{1}{2d}&[-(p-c_l)Q_{b3}^2 + 2(c_l Q_{r3} - pQ_{r3} - c_l d + pd - rd)Q_{b3} \\ &+ (c_l Q_{r3} - pQ_{r3} - 2c_l d + 2pd - 2w_3 d)Q_{r3}] \end{aligned}$$

It is not difficult to find that the aforementioned function is concave in Q_{b3} and its FOC solution is $Q_{b3} = d(p - c_l - r)/(p - c_l) - Q_{r3}$. Combined with the constraint condition (13), the optimal solution in the case of $\delta = 1$ is $Q_{b3} = \max(0, d(p - c_l - r)/(p - c_l) - Q_{r3})$.

Therefore, the optimal backup order decision of the retailer is

$$Q_{b3}^* = \begin{cases} \max(0, d(p - c_l - r)/(p - c_l) - Q_{r3}), & \delta = 1 \\ d(p - c_l - r)/(p - c_l), & \delta = 0 \end{cases} \tag{A2}$$

Substituting the first segment of (A2) into the first term of equation (14), and the second segment of that into the second term of (14), we have

$$\pi_3^R(Q_{r3}) = \begin{cases} a(r-w_3)Q_{r3} + \dfrac{d(p-c_l-r)^2}{2(p-c_l)}, & Q_{r3} < \dfrac{(p-c_l-r)d}{p-c_l} \\ -\dfrac{a(p-c_l)Q_{r3}^2}{2d} + a(p-c_l-w_3)Q_{r3} \\ \quad + \dfrac{d(1-a)(p-c_l-r)^2}{2(p-c_l)}, & Q_{r3} \ge \dfrac{(p-c_l-r)d}{p-c_l} \end{cases} \tag{A3}$$

It is not difficult to find that the aforementioned function is continuous, and the second segment of the function is concave and its FOC solution is $Q_{r3} = d(p - c_l - w_3)/(p - c_l)$. In order to obtain the optimal solution, two cases are discussed as follows:

(1) If $w_3 \le r$, the first segment of (A3) is increasing, and the FOC solution of the second segment satisfies $d(p - c_l - w_3)/(p - c_l) \ge d(p - c_l - r)/(p - c_l)$; that is, the second segment is a unimodal function. Thus, $\pi_3^R(Q_{r3})$ reaches its maximum at $Q_{r3} = d(p - c_l - w_3)/(p - c_l)$.

(2) If $w_3 > r$, the first segment of (A3) decreases, and the FOC solution of the second segment satisfies $d(p - c_l - w_3)/(p - c_l) < d(p - c_l - r)/(p - c_l)$; that is, the second segment also decreases. Thus, $\pi_3^R(Q_{r3})$ reaches its maximum at $Q_{r3} = 0$.

As a result, the retailer's optimal regular order quantity is

$$Q_{r3}^* = \begin{cases} d(p - c_l - w_3)/(p - c_l), & w_3 \le r \\ 0, & w_3 > r \end{cases} \tag{A4}$$

Substituting (A4) into (15), we have

$$\pi_3^M(w_3) = \begin{cases} \dfrac{d(w_3+c_l-p)(-aw_3+c+ac_l)}{p-c_l}, & w_3 \le r \\ 0, & w_3 > r \end{cases} \tag{A5}$$

It is not difficult to find that (A5) is discontinuous at $w_3 = r$ and $\pi_3^M(r) > 0$. In addition, the first segment of (A5) is concave and its FOC solution is $w_3 = (ap + c)/2a$. Thus, it is necessary to discuss the following cases:

(1) If $r \ge (ap + c)/2a$, the first segment of (A5) is unimodal. Thus, $\pi_3^M(w_3)$ reaches the maximum at $w_3 = (ap + c)/2a$.

(2) If $r < (ap + c)/2a$, the first segment of (A5) is increasing. Thus, $\pi_3^M(w_3)$ reaches the maximum at $w_3 = r$.

Therefore, the supplier's optimal wholesale price is

$$w_3^* = \begin{cases} (ap+c)/2a, & r \geq (ap+c)/2a \\ r, & r < (ap+c)/2a \end{cases} \tag{A6}$$

Combining (A2), (A4) and (A6), Lemma 3 is obtained. □

Proof of Corollary 2: According to Lemmas 1 and 3, we have

$$w_3^* - w_1^* = \begin{cases} 0, & r \geq (ap+c)\big/2a \\ r-(ap+c)\big/2a, & r < (ap+c)\big/2a \end{cases}$$

Thus, $w_3^* - w_1^* \leq 0$, or equivalently, $w_3^* \leq w_1^*$. Following the same argument, we have $Q_{r3}^* \geq Q_{r1}^*$. □

Proof of Lemma 4: To solve the program (17), two cases are discussed as follows.

(1) When $\delta = 1$, equation (17) can be rewritten as

$$\pi_{b4}^R = (p-c_l)\int_0^d \min(D, Q_{b4}+Q_{r4}) f(D)dD - w_4 Q_{r4} - rQ_{b4}$$

which can be simplified as

$$\pi_{b4}^R = -\frac{(p-c_l)(Q_{r4}+Q_{b4})(Q_{r4}+Q_{b4}-2d)}{2d} - rQ_{b4} - w_4 Q_{r4} \tag{A7}$$

Note that according to Assumption 1, we have

$$\frac{\partial^2 \pi_{b4}^R}{\partial Q_{b4}^2} = -\frac{p-c_l}{d} < 0$$

which means that π_{b4}^R can reaches its largest value at the FOC solution or endpoint. By equation (A7), it is not difficult to find that the FOC (first-order-condition) solution is

$$Q_{b4} = \frac{d(p-c_l-r)}{p-c_l} - Q_{r4}$$

Thus, combining with the constraint condition (18), we have

$$Q_{b4}^* = \max(0, \frac{d(p-c_l-r)}{p-c_l} - Q_{r4})$$

(2) When $\delta = 0$, equation (17) can be rewritten as

$$\pi_{b4}^R = (p-c_l)(\int_0^{Q_{b4}} \min(D, Q_{b4}) f(D)dD + \int_{Q_{b4}}^d \min(D, Q_{b4}) f(D)dD) - rQ_{b4}$$

which can be simplified as

$$\pi_{b4}^R = -\frac{(p-c_l)\,Q_{b4}\,(Q_{b4}-2d)}{2d} - rQ_{b4} \tag{A8}$$

Note that according to Assumption 1, we have

$$\frac{\partial^2 \pi_{b4}^R}{\partial Q_{b4}^2} = -\frac{p-c_l}{d} < 0$$

that is, equation (A8) is concave. The FOC solution of equation (A8) is

$$Q_{b4} = \frac{d\,(p-c_l-r)}{p-c_l}$$

According to Assumption (1), we have

$$\frac{d\,(p-c_l-r)}{p-c_l} > 0$$

Thus,

$$Q_{b4}^* = \frac{d\,(p-c_l-r)}{p-c_l}$$

In summary,

$$Q_{b4}^* = \begin{cases} \dfrac{d\,(p-c_l-r)}{p-c_l}, & \delta = 0 \\ \max(0, \dfrac{d(p-c_l-r)}{p-c_l} - Q_{r4}), & \delta = 1 \end{cases} \tag{A9}$$

Substituting equation (A9) into (19), we obtain

$$\pi_4^R = \begin{cases} a(r-w_4)Q_{r4} - \dfrac{d(-p+c_l+r)^2}{2(-p+c_l)}, & Q_{r4} < \dfrac{d(p-c_l-r)}{p-c_l} \\ -\dfrac{a(p-c_l)Q_{r4}^2}{2d} + a(p-c_l-w_4)Q_{r4} - \dfrac{(1-a)d(-p+c_l+r)^2}{2(-p+c_l)}, & Q_{r4} \geq \dfrac{d(p-c_l-r)}{p-c_l} \end{cases} \tag{A10}$$

Then two cases are discussed as follows.

(1) When $w_4 \leq r$, the first segment of equation (A10) is an increasing function. Furthermore, it is not difficult to find that the second segment of equation (A10) is concave according to Assumption 1, and its FOC solution is

$$Q_{r4} = \frac{(p-c_l-w_4)\,d}{p-c_l} \geq \frac{d(p-c_l-r)}{p-c_l}$$

Thus,

$$Q_{r4}^* = \frac{(p-c_l-w_4)\,d}{p-c_l}$$

(2) When $w_4 > r$, the first segment of equation (A10) is a decreasing function. Furthermore, it is not difficult to find that the second segment of equation (A10) is concave according to Assumption 1, and its FOC solution is

$$Q_{r4} = \frac{(p-c_l-w_4)\,d}{p-c_l} < \frac{d(p-c_l-r)}{p-c_l}$$

Thus,

$$Q_{r4}^* = 0$$

In summary,

$$Q_{r4}^* = \begin{cases} \dfrac{(p-c_l-w_4)\,d}{p-c_l}, & w_4 \leq r \\ 0, & w_4 > r \end{cases} \tag{A11}$$

Substituting equation (A11) into (20), we obtain

$$\pi_4^M = \begin{cases} \dfrac{(p-c_l-w_4)\,d\,(aw_4-c)}{p-c_l}, & w_4 \leq r \\ 0, & w_4 > r \end{cases} \tag{A12}$$

It is not difficult to find that equation (A12) is discontinuous at $w_4 = r$ and $\pi_4^M(r) > 0$ according to Assumption 1. In addition, the first segment of (A12) is concave and its FOC solution is $w_4 = ap - ac_l + c/2a$. Thus, it is necessary to discuss the following cases:

(1) If $r \geq (ap - ac_l + c)/2a$, the first segment of (A12) is unimodal. Thus, $\pi_4^M(w_4)$ reaches the maximum at $w_4 = (ap - ac_l + c)/2a$.

(2) If $r < (ap - ac_l + c)/2a$, the first segment of (A12) is increasing. Thus, $\pi_4^M(w_4)$ reaches the maximum at $w_4 = r$.

Therefore,

$$w_4^* = \begin{cases} (ap+c-ac_l)/2a, & r \geq (ap+c-ac_l)/2a \\ r, & r < (ap+c-ac_l)/2a \end{cases} \tag{A13}$$

Combining (A9), (A11) and (A13), Lemma 4 is obtained. □

Proof of Corollary 3: Since $w_4^* = \min(r, (ap+c-ac_l)/2a)$, in order to compare w_4^* and w_2^*, two cases are discussed as follows.

(1) If $c_l < (ap - c)/3a$, then

$$w_4^* = \begin{cases} (ap + c - ac_l)/2a, & r \geq (ap + c - ac_l)/2a \\ r, & r < (ap + c - ac_l)/2a \end{cases}$$

Thus,

$$w_4^* - w_2^* = \begin{cases} 0, & r \geq (ap + c - ac_l)/2a \\ r - ap + c - ac_l/2a, & r < (ap + c - ac_l)/2a \end{cases}$$

and

$$w_4^* - w_3^* = \begin{cases} -\dfrac{c_l}{2}, & r \geq \dfrac{ap+c}{2a} \\ \dfrac{ap+c-ac_l}{2a} - r, & \dfrac{ap+c-ac_l}{2a} \leq r < \dfrac{ap+c}{2a} \\ 0, & r < \dfrac{ap+c-ac_l}{2a} \end{cases}$$

As a result, $w_4^* \leq w_3^*$, $w_4^* \leq w_2^*$.

(2) If $c_l \geq (ap - c)/(3a)$, according to Assumption 2 we have $r > c_l + c/a \geq (ap + c - ac_l)/2a$, and $w_4^* = (ap + c - ac_l)/2a$. Then $w_4^* - w_2^* = 0$, and

$$w_4^* - w_3^* = \begin{cases} -c_l/2, & r \geq (ap + c)/2a \\ (ap + c - ac_l)/2a - r, & r < (ap + c)/2a \end{cases}$$

Thus, $w_4^* = w_2^*$, $w_4^* < w_3^*$.

Therefore, we have $w_4^* \leq w_2^*$ and $w_4^* \leq w_3^*$. Following the same argument, we have $Q_{r4}^* \geq Q_{r2}^*$ and $Q_{r4}^* \geq Q_{r3}^*$. □

Proof of Proposition 1: (1) Firstly, we prove $\pi_2^{R*} > \pi_1^{R*}$ as follows. Since

$$\pi_2^{R*} - \pi_1^{R*} = \frac{dc_l(3ac_l - 2ap + 2c)}{8(c_l - p)}$$

according to Assumptions 1 and 2, it is not difficult to find that $3ac_l - 2ap + 2c < 0$ and $c_l - p < 0$. Thus, $\pi_2^{R*} - \pi_1^{R*} > 0$, or equivalently, $\pi_2^{R*} > \pi_1^{R*}$.

(2) Secondly, we prove $\pi_4^{R*} \geq \pi_3^{R*}$ as follows. ① When $c_l \geq (ap - c)/(3a)$, we have $r \geq \frac{ap+c-ac_l}{2a}$, then $\pi_4^{R*} = \frac{d(ap-ac_l-c)^2}{8a(p-c_l)} + \frac{(1-a)d(p-c_l-r)^2}{2(p-c_l)}$. Thus,

$$\pi_4^{R*} - \pi_3^{R*} = \begin{cases} \dfrac{dc_l(2ap - 2c - 3ac_l)}{8(p - c_l)}, & r \geq \dfrac{ap + c}{2a} \\ \dfrac{d(ap + c - ac_l - 2ar)(3ac_l - 3ap + 2ar + c)}{8a(p - c_l)}, & r < \dfrac{ap + c}{2a} \end{cases}$$

According to Assumptions 1 and 2, the first segment of the aforementioned formula is greater than zero; furthermore, it is not difficult to find that the first derivative of the second segment with respect to r is greater than zero, i.e., it is increasing in r. Thus,

$$\frac{d(ap+c-ac_l-2ar)(3ac_l-3ap+2ar+c)}{8a(p-c_l)} > \frac{d(ap+c-ac_l-2a\frac{ap+c-ac_l}{2a})(3ac_l-3ap+2a\frac{ap+c-ac_l}{2a}+c)}{8a(p-c_l)} = 0$$

Then we have $\pi_4^{R*} - \pi_3^{R*} > 0$.

② When $c_l < (ap - c)/(3a)$,

$$\pi_4^{R*} = \begin{cases} \dfrac{dp(ap - ac_l - c)^2}{2a(2p - c_l)^2} + \dfrac{(1 - a)d(p - c_l - r)^2}{2(p - c_l)}, & r \geq (ap + c - ac_l)/2a \\ \dfrac{d(p - c_l - r)^2}{2(p - c_l)}, & r < (ap + c - ac_l)/2a \end{cases}$$

Then

$$\pi_4^{R*} - \pi_3^{R*} = \begin{cases} \dfrac{dc_l(2ap-2c-3ac_l)}{8(p-c_l)}, & r \geq \dfrac{ap+c}{2a} \\ \dfrac{d(ap+c-ac_l-2ar)(3ac_l-3ap+2ar+c)}{8a(p-c_l)}, & r < \dfrac{ap+c}{2a} \\ 0, & r < \dfrac{ap+c-ac_l}{2a} \end{cases}$$

It has been proved that both the first and the second segment of the aforementioned formula are greater than zero. Thus, $\pi_4^{R*} - \pi_3^{R*} > 0$.

(3) Thirdly, we prove $\pi_3^{R*} > \pi_1^{R*}$ as follows. Note that

$$\pi_3^{R*} - \pi_1^{R*} = \begin{cases} \dfrac{(1 - a)d(c_l + r - p)^2}{2(p - c_l)}, & r \geq \dfrac{ap + c}{2a} \\ \dfrac{d(c_l + r - p)^2}{2(p - c_l)} - \dfrac{d(2ac_l - ap + c)^2}{8a(p - c_l)}, & r < \dfrac{ap + c}{2a} \end{cases}$$

The first segment of the aforementioned formula is greater than zero; furthermore, it is not difficult to find that the first derivative of the second segment with respect to r is less than zero, i.e., it is decreasing in r. Thus,

$$\frac{d(c_l + r - p)^2}{2(p - c_l)} - \frac{d(2ac_l - ap + c)^2}{8a(p - c_l)}$$

$$> \frac{d(c_l + \frac{ap+c}{2a} - p)^2}{2(p-c_l)} - \frac{d(2ac_l - ap + c)^2}{8a(p-c_l)}$$
$$= \frac{(1-a)d(2ac_l - ap + c)^2}{8a^2(p-c_l)} > 0$$

Then we have $\pi_3^{R*} - \pi_1^{R*} > 0$, i.e., $\pi_3^{R*} > \pi_1^{R*}$.

(4) Finally, we prove $\pi_4^{R*} > \pi_2^{R*}$ as follows. ① When $c_l \geq (ap-c)/(3a)$, we have $r \geq \frac{ap+c-ac_l}{2a}$, then

$$\pi_4^{R*} = \frac{d(ap-ac_l-c)^2}{8a(p-c_l)} + \frac{(1-a)d(p-c_l-r)^2}{2(p-c_l)}$$

So

$$\pi_4^{R*} - \pi_2^{R*} = \frac{(1-a)d(c_l+r-p)^2}{2(p-c_l)} > 0$$

② When $c_l < (ap-c)/(3a)$,

$$\pi_4^{R*} = \begin{cases} \frac{dp(ap-ac_l-c)^2}{2a(2p-c_l)^2} + \frac{(1-a)d(p-c_l-r)^2}{2(p-c_l)}, & r \geq (ap+c-ac_l)/2a \\ \frac{d(p-c_l-r)^2}{2(p-c_l)}, & r < (ap+c-ac_l)/2a \end{cases}$$

so that

$$\pi_4^{R*} - \pi_2^{R*} = \begin{cases} \frac{(1-a)d(p-c_l-r)^2}{2(p-c_l)}, & r \geq (ap+c-ac_l)/2a \\ \frac{d(p-c_l-r)^2}{2(p-c_l)} - \frac{d(ap-ac_l+c)^2}{8a(p-c_l)}, & r < (ap+c-ac_l)/2a \end{cases}$$

The first segment of the aforementioned formula is greater than zero; furthermore, it is not difficult to find that the first derivative of the second segment with respect to r is less than zero, i.e., it is decreasing in r. Thus,

$$\frac{d(p-c_l-r)^2}{2(p-c_l)} - \frac{d(ap-ac_l+c)^2}{8a(p-c_l)}$$
$$> \frac{d(p-c_l+(ap+c-ac_l)/2a)^2}{2(p-c_l)} - \frac{d(ap-ac_l+c)^2}{8a(p-c_l)}$$
$$= \frac{(1-a)d(ap-ac_l-c)^2}{8a^2(p-c_l)} > 0$$

Then $\pi_4^{R*} - \pi_2^{R*} > 0$. □

Proof of Proposition 2: (1) When $c_l \geq (ap-c)/(3a)$,

$$\begin{aligned} &V_{db}^R - V_b^R \\ &= \pi_4^{R*} - \pi_2^{R*} - (\pi_3^{R*} - \pi_1^{R*}) \\ &= \begin{cases} 0, & r \geq \frac{ap+c}{2a} \\ \frac{d(ap+c-2ar)(4ac_l-3ap+2ar+c)}{8a(p-c_l)}, & r < \frac{ap+c}{2a} \end{cases} \end{aligned} \tag{A14}$$

Since

$$ap + c - 2ar > ap + c - 2a \cdot \frac{ap+c}{2a} = 0$$

and

$$4ac_l - 3ap + 2ar + c < 4ac_l - 3ap + 2a\frac{ap+c}{2a} + c = 0$$

the second segment of equation (A14) is less than zero; that is, $\pi_4^{R*} - \pi_2^{R*} - (\pi_3^{R*} - \pi_1^{R*}) \leq 0$.

(2) When $c_l < (ap-c)/(3a)$,

$$\begin{aligned} &V_{db}^R - V_b^R \\ &= \pi_4^{R*} - \pi_2^{R*} - (\pi_3^{R*} - \pi_1^{R*}) \\ &= \begin{cases} 0, & r \geq \frac{ap+c}{2a} \\ \frac{d(ap+c-2ar)(4ac_l-3ap+2ar+c)}{8a(p-c_l)}, & \frac{ap+c-ac_l}{2a} \leq r < \frac{ap+c}{2a} \\ \frac{dc_l(3ac_l-2ap+2c)}{8(p-c_l)}, & r < \frac{ap+c-ac_l}{2a} \end{cases} \end{aligned}$$

It has been proved that the second segment of the above formula is less than zero. Furthermore, according to Assumptions 1 and 2, the third segment of the above formula is also less than zero. Thus, $\pi_4^{R*} - \pi_2^{R*} - (\pi_3^{R*} - \pi_1^{R*}) \leq 0$.

Therefore, we have $\pi_4^{R*} - \pi_2^{R*} \leq \pi_3^{R*} - \pi_1^{R*}$, i.e., $V_{bd}^R \leq V_b^R$. In addition, $\pi_4^{R*} - \pi_2^{R*} \leq \pi_3^{R*} - \pi_1^{R*}$ is equivalent to $\pi_4^{R*} - \pi_3^{R*} \leq \pi_2^{R*} - \pi_1^{R*}$, i.e., $V_{bd}^R \leq V_d^R$. According to the definition of substitutability and complementarity given by [30] and [31], the drop-shipping and backup-sourcing are substitutive strategies. □

Proof of Proposition 3: (1) Firstly, we prove $\pi_2^{M*} > \pi_1^{M*}$ as follows. Since

$$\pi_2^{M*} - \pi_1^{M*} = \frac{dc_l(2ap-2c-3ac_l)}{4(p-c_l)}$$

according to Assumptions 1 and 2, it is not difficult to find that $2ap - 2c - 3ac_l > 0$, therefore, $\pi_2^{M*} > \pi_1^{M*}$.

(2) Secondly, we prove $\pi_4^{M*} > \pi_3^{M*}$ as follows. ① When $c_l \geq (ap-c)/(3a)$, by (22), we have

$$\pi_4^{M*} - \pi_3^{M*} = \begin{cases} \frac{dc_l(2ap-2c-3ac_l)}{4(p-c_l)}, & r \geq \frac{ap+c}{2a} \\ \frac{d(ap-ac_l-c)^2}{4a(p-c_l)} - \frac{d(p-c_l-r)(ar-ac_l-c)}{p-c_l}, & r < \frac{ap+c}{2a} \end{cases}$$

According to Assumptions 1 and 2, the first segment of the above formula is greater than zero. Moreover, it is not difficult to find that the first derivative of the second segment of the above formula is less than zero; that is, it is decreasing in r. Then

$$\frac{d(ap-ac_l-r)^2}{4a(p-c_l)} - \frac{d(p-c_l-r)(ar-ac_l-c)^2}{p-c_l}$$
$$> \frac{d(ap-ac_l-c)^2}{4a(p-c_l)} - \frac{d(p-c_l-\frac{ap+c}{2a})(a\frac{ap+c}{2a}-ac_l-c)}{p-c_l}$$
$$= \frac{dc_l(2ap-2c-3ac_l)}{4(p-c_l)} > 0$$

Thus, $\pi_4^{M*}-\pi_3^{M*}>0$. ② When $c_l<(ap-c)/(3a)$, according to (21), we have

$$\pi_4^{M*}-\pi_3^{M*}=\begin{cases}\dfrac{dc_l(2ap-2c-3ac_l)}{4(p-c_l)}, & r\ge\dfrac{ap+c}{2a}\\ \dfrac{d(ap-ac_l-c)^2}{4a(p-c_l)}-\dfrac{d(p-c_l-r)(ar-ac_l-c)}{p-c_l}, & \dfrac{ap+c-ac_l}{2a}\le r<\dfrac{ap+c}{2a}\\ \dfrac{adc_l(p-r-c_l)}{p-c_l}, & r<\dfrac{ap+c-ac_l}{2a}\end{cases}$$

The first segment and the second segment of the aforementioned formula have been proved to be greater than zero. According to the Assumption 1, the third segment of the above formula is also greater than zero. Therefore, $\pi_4^{M*}-\pi_3^{M*}>0$.

(3) Thirdly, we prove $\pi_3^{M*}\le\pi_1^{M*}$ as follows. Since

$$\pi_3^{M*}-\pi_1^{M*}=\begin{cases}0, & r\ge\dfrac{ap+c}{2a}\\ -\dfrac{d(ap-2ar+c)^2}{4a(p-c_l)}, & r<\dfrac{ap+c}{2a}\end{cases}$$

we have $\pi_3^{M*}-\pi_1^{M*}\le 0$.

(4) Finally, we prove $\pi_4^{M*}\le\pi_2^{M*}$as follows. Since

$$\pi_4^{M*}-\pi_2^{M*}=\begin{cases}0, & r\ge\dfrac{ap+c-ac_l}{2a}\\ -\dfrac{d(ap-2ar+c-ac_l)^2}{4a(p-c_l)}, & r<\dfrac{ap+c-ac_l}{2a}\end{cases}$$

we have $\pi_4^{M*}-\pi_2^{M*}\le 0$. □

Proof of Proposition 4: Since $V_{db}^M-V_b^M=\pi_4^{M*}-\pi_2^{M*}-(\pi_3^{M*}-\pi_1^{M*})$, then according to (6), (12), (16), and (21), we have

$$\pi_4^{M*}-\pi_2^{M*}-(\pi_3^{M*}-\pi_1^{M*})=\begin{cases}0, & r\ge\dfrac{ap+c}{2a}\\ \dfrac{d(ap-2ar+c)^2}{4a(p-c_l)}, & \dfrac{ap+c-ac_l}{2a}\le r<\dfrac{ap+c}{2a}\\ \dfrac{dc_l(2ap-ac_l-4ar+2c)}{4(p-c_l)}, & r<\dfrac{ap+c-ac_l}{2a}\end{cases}$$

It is not difficult to find that the second and third segments of the aforementioned formula are greater than zero. Thus, $\pi_4^{M*}-\pi_2^{M*}-(\pi_3^{M*}-\pi_1^{M*})\ge 0$, i.e., $V_{db}^M\ge V_b^M$. Note that

$$\begin{aligned}V_{bd}^M-V_d^M&=\pi_4^{M*}-\pi_3^{M*}-(\pi_2^{M*}-\pi_1^{M*})\\&=\pi_4^{M*}-\pi_2^{M*}-(\pi_3^{M*}-\pi_1^{M*})\\&=V_{db}^M-V_b^M\end{aligned}$$

Therefore, $V_{bd}^M\ge V_d^M$. According to the definition of complementarity given by [30] and [31], there is complementarity between the backup-sourcing and drop-shipping strategies for the supplier. □

Proof of Proposition 5: (1) When$c_l\ge(ap-c)/(2a)$,

$$V_{db}^S-V_b^S=\begin{cases}0, & r\ge\dfrac{ap+c}{2a}\\ \dfrac{d(ap+c-2ar)(4ac_l-ap-2ar+3c)}{8a(p-c_l)}, & r<\dfrac{ap+c}{2a}\end{cases}$$

According to Assumptions 1 and 2, it is not difficult to find that $8a(p-c_l)>0$ and $ap+c-2ar>0$. Since $(4ac_l-ap+3c)/(2a)<(ap+c)/(2a)$, two cases are discussed as follows. Firstly, if $r\ge(4ac_l-ap+3c)/(2a)$, we have $4ac_l-ap-2ar+3c\le 0$ which means that $V_{db}^S\le V_b^S$ or equivalently, $V_{bd}^S\le V_d^S$. Secondly, if $r<(4ac_l-ap+3c)/(2a)$, we have $4ac_l-ap-2ar+3c>0$, which means that $V_{db}^S>V_b^S$ or equivalently, $V_{bd}^S>V_d^S$.

(2) When $2(ap-c)/(7a)\le c_l<(ap-c)/(2a)$, two cases are discussed as follows. Firstly, if, $(ap-c)/(3a)\le c_l<(ap-c)/(2a)$,

$$V_{db}^S-V_b^S=\begin{cases}0, & r\ge\dfrac{ap+c}{2a}\\ \dfrac{d(ap+c-2ar)(4ac_l-ap-2ar+3c)}{8a(p-c_l)}, & r<\dfrac{ap+c}{2a}\end{cases}$$

Since $r>c/a+c_l>(4ac_l-ap+3c)/(2a)$, we have $4ac_l-ap-2ar+3c<0$, which means that $V_{db}^S\le V_b^S$ or equivalently, $V_{bd}^S\le V_d^S$. Secondly, if $2(ap-c)/(7a)\le c_l<(ap-c)/(3a)$,

$$V_{db}^S-V_b^S=\begin{cases}0, & r\ge\dfrac{ap+c}{2a}\\ \dfrac{d(ap+c-2ar)(4ac_l-ap-2ar+3c)}{8a(p-c_l)}, & \dfrac{ap+c-ac_l}{2a}\le r<\dfrac{ap+c}{2a}\\ \dfrac{dc_l(ac_l+2ap+6c-8ar)}{8(p-c_l)}, & r<\dfrac{ap+c-ac_l}{2a}\end{cases}$$

For the second segment of the above formula, it is not difficult to find that $r\ge(ap+c-ac_l)/(2a)>(4ac_l-ap+3c)/(2a)$, i.e., $4ac_l-ap-2ar+3c<0$; For the third segment of the the formula, it is not difficult to find that $r>c/a+c_l>(ac_l+2ap+6c)/8a$, i.e., $ac_l+2ap+6c-8ar<0$; thus, $V_{db}^S\le V_b^S$ or equivalently, $V_{bd}^S\le V_d^S$.

(3) When $c_l<2(ap-c)/(7a)$,

$$V_{db}^S-V_b^S=\begin{cases}0, & r\ge\dfrac{ap+c}{2a}\\ \dfrac{d(ap+c-2ar)(4ac_l-ap-2ar+3c)}{8a(p-c_l)}, & \dfrac{ap+c-ac_l}{2a}\le r<\dfrac{ap+c}{2a}\\ \dfrac{dc_l(ac_l+2ap+6c-8ar)}{8(p-c_l)}, & r<\dfrac{ap+c-ac_l}{2a}\end{cases}\tag{A15}$$

It has been proved that the second segment of the above equation is less than zero. Since $(ac_l + 2ap + 6c)/8a < (ap + c - ac_l)/2a$, two cases are discussed as follows. Firstly, if $r \geq (ac_l + 2ap + 6c)/(8a)$, i.e., $ac_l + 2ap + 6c - 8ar \leq 0$, the third segment of (A15) is less than zero; that is, $V_{db}^S \leq V_b^S$or equivalently, $V_{db}^S \leq V_d^S$. Secondly, if, $r < (ac_l + 2ap + 6c)/(8a)$i.e., $ac_l + 2ap + 6c - 8ar > 0$, we have

$$V_{db}^S - V_b^S = \frac{dc_l(ac_l + 2ap + 6c - 8ar)}{8(p - c_l)} > 0$$

that is, $V_{db}^S > V_b^S$ or equivalently $V_{bd}^S > V_d^S$. □

Proof of Lemma 5: Through backward induction, we first analyze the backup order decision of the retailer. Recall that the retailer's decision problem is as follows:

$$\begin{aligned} \max_{Q_{b4}} \ \pi_{b4}^R &= E_D[p \cdot \min(D, Q_{b4} + \delta Q_{r4}) - w_4 \delta Q_{r4} \\ &\quad - rQ_{b4} - c_l(\min(D, Q_{b4} + \delta Q_{r4}))] \\ \text{s.t. } & Q_{b4} \geq 0 \end{aligned} \tag{A16}$$

To solve the above program, two cases are discussed as follows.

(1) When $\delta = 1$, equation (A16) can be rewritten as

$$\pi_{b4}^R = (p - c_l)\int_0^d \min(D, Q_{b4} + Q_{r4})f(D)dD - w_4 Q_{r4} - rQ_{b4}$$

Then we have

$$\begin{aligned} \pi_{b4}^R &= (p - c_l)\Big(\int_0^{Q_{b4}+Q_{r4}} \min(D, Q_{b4} + Q_{r4})f(D)dD \\ &\quad + \int_{Q_{b4}+Q_{r4}}^d \min(D, Q_{b4} + Q_{r4})f(D)dD\Big) - w_4 Q_{r4} \\ &\quad - rQ_{b4} \end{aligned}$$

which can be simplified as

$$\begin{aligned} \pi_{b4}^R &= (p - c_l)(Q_{b4} + \delta Q_{r4} - \int_0^{Q_{b4}+\delta Q_{r4}} F(D)dD) \\ &\quad - w_4 \delta Q_{r4} - rQ_{b4} \end{aligned} \tag{A17}$$

Note that

$$\frac{\partial^2 \pi_{b4}^R}{\partial Q_{b4}^2} = -(p - c_l)f(Q_{b4} + Q_{r4}) < 0$$

π_{b4}^R can reaches its largest value at the FOC solution or endpoint. By equation (A17), it is not difficult to find that the FOC solution is:

$$Q_{b4} = F^{-1}(1 - \frac{r}{p - c_l}) - Q_{r4}$$

Thus,

$$Q_{b4}^* = \max(0, F^{-1}(1 - \frac{r}{p - c_l}) - Q_{r4})$$

(2) When $\delta = 0$, equation (A16) can be rewritten as

$$\begin{aligned} \pi_{b4}^R &= (p - c_l)\Big(\int_0^{Q_{b4}} \min(D, Q_{b4})f(D)dD \\ &\quad + \int_{Q_{b4}}^d \min(D, Q_{b4})f(D)dD\Big) - rQ_{b4} \end{aligned}$$

which can be simplified as

$$\pi_{b4}^R = (p - c_l)(Q_{b4} - \int_0^{Q_{b4}} F(D)dD) - rQ_{b4}$$

It is not difficult to find that the above equation is concave, and the FOC solution is:

$$Q_{b4} = F^{-1}(1 - \frac{r}{p - c_l}) > 0$$

Thus,

$$Q_{b4}^* = F^{-1}(1 - \frac{r}{p - c_l})$$

In summary,

$$Q_{b4}^* = \begin{cases} F^{-1}(1 - \frac{r}{p - c_l}), & \delta = 0 \\ \max(0, F^{-1}(1 - \frac{r}{p - c_l}) - Q_{r4}), & \delta = 1 \end{cases} \tag{A18}$$

Next, we analyze the regular order decision of the retailer. Recall that the retailer's decision problem is as follows:

$$\begin{aligned} \max_{Q_{r4}} \ \pi_4^R &= aE_D[p \cdot \min(D, Q_{b4} + Q_{r4}) - w_4 Q_{r4} - rQ_{b4} - c_l \\ &\quad \cdot (\min(D, Q_{b4} + Q_{r4}))] + (1 - a)E_D[p \\ &\quad \cdot \min(D, Q_{b4}) - rQ_{b4} - c_l(\min(D, Q_{b4}))] \\ \text{s.t. } & V_{db}^R \leq V_b^R \end{aligned} \tag{A19}$$

Substituting equation (A18) into (A19), we obtain

$$\begin{aligned} \pi_4^R &= a(p - c_l)[\max(Q_{r4}, m) - \int_0^{\max(Q_{r4}, m)} F(D)dD] - aw_4 Q_{r4} \\ &\quad - ar \cdot \max(0, m - Q_{r4}) + (1 - a)(p - c_l)(m \\ &\quad - \int_0^m F(D)dD) - (1 - a)rm \end{aligned}$$

which can be simplified as

$$\pi_4^R = \begin{cases} (p - c_l)(m - \int_0^m F(D)dD) + a(r - w_4)Q_{r4} - rm, \\ \quad Q_{r4} < m \\ a(p - c_l)[Q_{r4} - \int_0^{Q_{r4}} F(D)dD] - aw_4 Q_{r4} \\ \quad + (1 - a)(p - c_l)(m - \int_0^m F(D)dD) - (1 - a)rm, \\ \quad Q_{r4} \geq m \end{cases} \tag{A20}$$

where $m = F^{-1}(1 - r/p - c_l)$. The above piecewise function is continuous (at $Q_{r4} = m$). Then two cases are discussed as follows.

(1) When $w_4 \leq r$, the first segment of equation (A20) is an increasing function. Furthermore, it is not difficult to find

that the second segment of equation (A20) is concave and its FOC solution is

$$Q_{r4} = F^{-1}(1 - \frac{w_4}{p - c_l}) \geq F^{-1}(1 - \frac{r}{p - c_l})$$

Thus,

$$Q_{r4}^* = F^{-1}(1 - \frac{w_4}{p - c_l})$$

(2) When $w_4 > r$, the first segment of equation (A20) is a decreasing function. Furthermore, it is not difficult to find that the second segment of equation (A20) is concave and its FOC solution is

$$Q_{r4} = F^{-1}(1 - \frac{w_4}{p - c_l}) < F^{-1}(1 - \frac{r}{p - c_l})$$

Thus,

$$Q_{r4}^* = 0$$

In summary,

$$Q_{r4}^* = \begin{cases} F^{-1}(1 - \frac{w_4}{p - c_l}), & w_4 \leq r \\ 0, & w_4 > r \end{cases} \quad \text{(A21)}$$

Finally, we analyze the wholesale price decision of the supplier. Recall that the supplier's decision problem is as follows:

$$\max_{w_4} \pi_4^M = aw_4 Q_{r4} - cQ_{r4} \quad \text{(A22)}$$

Substituting equation (A21) into (A22), we obtain

$$\pi_4^M = \begin{cases} (aw_4 - c)F^{-1}(1 - \frac{w_4}{p - c_l}), & w_4 \leq r \\ 0, & w_4 > r \end{cases}$$

Note that if $aw_4 - c > 0$ and $1 - w_4/(p - c_l) > 0$ (i.e., $c/a < w_4 < p - c_l$), the first segment of above function is always greater than zero. According to Assumption 1, there always exists w_4 satisfying $c/a < w_4 < p - c_l$, thus, the optimal solution must be in the first segment of the above function. Therefore,

$$w_4^* = \min(\beta, r) \quad \text{(A23)}$$

where

$$w^* = \arg\max(aw - c)F^{-1}[1 - \frac{w}{p - c_l}]$$

Combining (A18), (A21) and (A23), Lemma 5 is obtained. □

REFERENCES

[1] P. R. Kleindorfer and G. H. Saad, "Managing disruption risks in supply chains," *Prod. Oper. Manage.*, vol. 14, no. 1, pp. 53–68, Jan. 2009.
[2] M. Wang, T. Tian, and X. Zhu, "Self-remanufacturing or outsourcing? Hybrid manufacturing system with remanufacturing options under yield uncertainty," *IEEE Access*, vol. 7, pp. 150642–150656, 2019.
[3] Q. Gao, D. Xia, Y. Shi, and J. Quan, "Policies adoption for supply disruption mitigation based on customer segmentation," *IEEE Access*, vol. 7, pp. 47329–47338, 2019.
[4] D.-Q. Yao, H. Kurata, and S. K. Mukhopadhyay, "Incentives to reliable order fulfillment for an Internet drop-shipping supply chain," *Int. J. Prod. Econ.*, vol. 113, no. 1, pp. 324–334, May 2008.
[5] T. Cheong, M. Goh, and S. H. Song, "Effect of inventory information discrepancy in a drop-shipping supply chain," *Decis. Sci.*, vol. 46, no. 1, pp. 193–213, Feb. 2015.
[6] M. Zhel. *Best Drop-shipping Companies*. Accessed: Oct. 2016. [Online]. Available: https://mofluid.com/blog/10-best-drop-shipping-companies/
[7] M. Khouja, "The evaluation of drop shipping option for e-commerce retailers," *Comput. Ind. Eng.*, vol. 41, no. 2, pp. 109–126, Nov. 2001.
[8] S. Netessine and N. Rudi, "Supply chain choice on the Internet," *Manage. Sci.*, vol. 52, no. 6, pp. 844–864, Jun. 2006.
[9] X. Gan, S. P. Sethi, and J. Zhou, "Commitment-penalty contracts in drop-shipping supply chains with asymmetric demand information," *Eur. J. Oper. Res.*, vol. 204, no. 3, pp. 449–462, Aug. 2010.
[10] W. K. Chiang and Y. Feng, "Retailer or e-tailer? Strategic pricing and economic-lot-size decisions in a competitive supply chain with drop-shipping," *J. Oper. Res. Soc.*, vol. 61, no. 11, pp. 1645–1653, Nov. 2010.
[11] D. Z. Yu, T. Cheong, and D. Sun, "Impact of supply chain power and drop-shipping on a manufacturer's optimal distribution channel strategy," *Eur. J. Oper. Res.*, vol. 259, no. 2, pp. 554–563, Jun. 2017.
[12] B. Tomlin, "On the value of mitigation and contingency strategies for managing supply chain disruption risks," *Manage. Sci.*, vol. 52, no. 5, pp. 639–657, May 2006.
[13] P. Kouvelis and J. Li, "Flexible backup supply and the management of lead-time uncertainty," *Prod. Oper. Manage.*, vol. 17, no. 2, pp. 184–199, Mar. 2008.
[14] J. Hou, A. Z. Zeng, and L. Zhao, "Coordination with a backup supplier through buy-back contract under supply disruption," *Transp. Res. E*, vol. 46, no. 6, pp. 881–895, Nov. 2010.
[15] K. Chen and L. Yang, "Random yield and coordination mechanisms of a supply chain with emergency backup sourcing," *Int. J. Prod. Res.*, vol. 52, no. 16, pp. 4747–4767, Aug. 2014.
[16] K. Chen and T. Xiao, "Production planning and backup sourcing strategy of a buyer-dominant supply chain with random yield and demand," *Int. J. Syst. Sci.*, vol. 46, no. 15, pp. 2799–2817, Nov. 2015.
[17] A. Z. Zeng and Y. Xia, "Building a mutually beneficial partnership to ensure backup supply," *Omega*, vol. 52, pp. 77–91, Apr. 2015.
[18] S. Guo, L. Zhao, and X. Xu, "Impact of supply risks on procurement decisions," *Ann. Oper. Res.*, vol. 241, nos. 1–2, pp. 411–430, Jun. 2016.
[19] M. Kamalahmadi and M. M. Parast, "An assessment of supply chain disruption mitigation strategies," *Int. J. Prod. Econ.*, vol. 184, pp. 210–230, Feb. 2017.
[20] Z. Yin and C. Wang, "Strategic cooperation with a backup supplier for the mitigation of supply disruptions," *Int. J. Prod. Res.*, vol. 56, no. 12, pp. 4300–4312, Jun. 2018.
[21] H. Du and Y. Jiang, "Backup or reliability improvement strategy for a manufacturer facing heterogeneous consumers in a dynamic supply chain," *IEEE Access*, vol. 7, pp. 50419–50430, 2019.
[22] E. L. Porteus, "The optimality of generalized (s, S) policies under uniform demand densities," *Manage. Sci.*, vol. 18, no. 11, pp. 644–646, Jul. 1972.
[23] G. J. Burke, J. E. Carrillo, and A. J. Vakharia, "Sourcing decisions with stochastic supplier reliability and stochastic demand," *Prod. Oper. Manage.*, vol. 18, no. 4, pp. 475–484, Jul. 2009.
[24] O. Berman and D. Krass, "On n-facility median problem with facilities subject to failure facing uniform demand," *Discrete Appl. Math.*, vol. 159, no. 6, pp. 420–432, Mar. 2011.
[25] N. A. Kurdhi, M. Marchamah, and Respatiwulan, "A two-echelon supply chain inventory model with shortage backlogging, inspection errors and uniform demand under imperfect quality items," *Int. J. Procurement Manage.*, vol. 11, no. 2, pp. 135–152, 2018.
[26] Y. Qin, R. Wang, A. J. Vakharia, Y. Chen, and M. M. H. Seref, "The newsvendor problem: Review and directions for future research," *Eur. J. Oper. Res.*, vol. 213, no. 2, pp. 361–374, Sep. 2011.
[27] Z. B. Yang, G. Aydın, V. Babich, and D. R. Beil, "Supply disruptions, asymmetric information, and a backup production option," *Manage. Sci.*, vol. 55, no. 2, pp. 192–209, Feb. 2009.
[28] L. Qi, "A continuous-review inventory model with random disruptions at the primary supplier," *Eur. J. Oper. Res.*, vol. 225, no. 1, pp. 59–74, Feb. 2013.
[29] N. Zeng and Q. He, "Dual sourcing strategy for high-tech manufacturer under supply risk and capacity constraint," *IEEE Access*, vol. 7, pp. 42672–42682, 2019.
[30] D. M. Topkis, "Minimizing a submodular function on a lattice," *Oper. Res.*, vol. 26, no. 2, pp. 305–321, Apr. 1978.

[31] C.-H.-S. Lee, A. Barua, and A. B. Whinston, "The complementarity of mass customization and electronic commerce," *Econ. Innov. New Technol.*, vol. 9, no. 2, pp. 81–110, Jan. 2000.
[32] S. Shi, J. Sun, and T. C. E. Cheng, "Wholesale or drop-shipping: Contract choices of the online retailer and the manufacturer in a dual-channel supply chain," *Int. J. Prod. Econ.*, vol. 226, no. 8, pp. 1–17, 2020.
[33] S. Ma and Z. Jemai, "Inventory rationing for the news-vendor problem with a drop-shipping option," *Appl. Math. Model.*, vol. 71, pp. 438–451, Jul. 2019.
[34] K. Zeng, Y. Gong, and X. Xu, "Supply chain choice with financial constraints on the Internet: Drop shipping vs. traditional channel," *Comput. Ind. Eng.*, vol. 137, pp. 1–13, Nov. 2019.
[35] S. Li, Y. He, and L. Chen, "Dynamic strategies for supply disruptions in production-inventory systems," *Int. J. Prod. Econ.*, vol. 194, pp. 88–101, Dec. 2017.
[36] Y. He, S. Li, H. Xu, and C. Shi, "An in-depth analysis of contingent sourcing strategy for handling supply disruptions," *IEEE Trans. Eng. Manag.*, vol. 67, no. 1, pp. 201–219, Feb. 2020.
[37] J. Hou and L. Zhao, "Backup agreements with penalty scheme under supply disruptions," *Int. J. Syst. Sci.*, vol. 43, no. 5, pp. 987–996, May 2012.
[38] X. Zhang and J. Wu, "Evaluation of reliability of distribution service based on Markov process," *Ind. Eng. J.*, vol. 9, no. 5, pp. 11–14, 2006.
[39] G. P. Cachon and M. A. Lariviere, "Contracting to assure supply: How to share demand forecasts in a supply chain," *Manage. Sci.*, vol. 47, no. 5, pp. 629–646, May 2001.
[40] Z. E. Li, Q. Lu, and M. Talebian, "Online versus bricks-and-mortar retailing: A comparison of price, assortment and delivery time," *Int. J. Prod. Res.*, vol. 53, no. 13, pp. 3823–3835, Jul. 2015.

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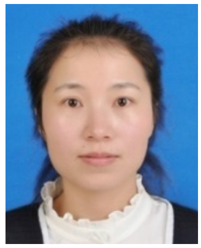

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