The comparison of two procurement strategies in the presence of supply disruption
Bo He a,⇑, He Huang a, Kaifu Yuan b

a School of Economics & Business Administration, Chongqing University, Chongqing 400030, China
b School of Business & Management, Guizhou University of Finance & Economics, Guiyang 550004, China

A R T I C L E   I N F O

Article history:
Received 2 July 2014
Received in revised form 25 March 2015
Accepted 26 March 2015
Available online 3 April 2015

Keywords:
Supply disruption
Procurement
Game theory
Supply chain

A B S T R A C T

The emergency procurement strategy and the optimal allocation procurement strategy are widely used for managing supply disruption risks. In this paper, we investigate two competing manufacturers using these procurement strategies in the presence of supply disruption risks. The joint pricing and ordering decisions of both manufacturers are analyzed using the game theoretic framework. The structural property of the manufacturer with the optimal allocation procurement strategy is characterized by the reliability threshold value, which further determines the equilibrium outcomes for both manufacturers. We find the reliability threshold is a generalization of the supplier's reliability level, which involves all the critical factors that influence manufacturers' procurement decisions under a competitive scenario. The optimal allocation procurement strategy for manufacturer profit maximization in a non-competitive scenario does not necessarily generate competitive advantage in a competitive scenario; under a wide range of parameters, the emergency procurement strategy can produce larger profit for the manufacturer than the optimal allocation procurement strategy when all suppliers are unreliable. The effects of reliability level and costs on procurement decisions are examined using comparative studies and numerical computations.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Supply disruptions present a real business challenge. Such disruptions may lead to defaults by the suppliers that provide manufacturers with inputs necessary to their production. For example, in April 2010, a volcanic eruption in Iceland shut down production plants all over the world that required key parts from Europe. BBC News reported that Nissan stopped production of three auto models in Japan and BMW cut production in Germany. A 2011 survey found that 85% of manufacturers had suffered multiple supply disruptions (Veysey, 2011).

Supply disruptions can occur for numerous reasons, such as earthquakes, power failures, and terrorist attacks. Increasing price competition, outsourcing and offshoring are driving manufacturers to source from more inexpensive suppliers even when they have imperfect reliability. Therefore, the management of supply risks has become a critical challenge for procurement managers in today’s globalized and highly uncertain business environment. Supply risk management has become increasingly important to supply chain management.

To mitigate the negative effects of supply disruption, numerous management strategies have been studied, such as dual-sourcing, emergency sourcing, backup supply, demand management, increasing safety stock, and improving supplier process (Sheffi, 2005; Tang & Kouvelis, 2011; Tomlin, 2006, 2009a, 2009b; Wang, Gilland, & Tomlin, 2010). Although an increasing number of papers have examined supply disruption, most have focused on its effect on manufacturer performance and how to employ operational strategies to mitigate supply risk from the perspective of a single firm. Thus the question remains of what will occur if manufacturers adopt distinct operational strategies to compete under supply disruption risks. Hence, in this paper we study horizontal competition between manufacturers employing distinct procurement strategies. Additionally, when something is in short supply, the price will differ relative to when it is in full supply. For example, on September 21, 1999, a major earthquake in Taiwan caused a tripling of computer memory prices on world markets. Therefore, the effect of supply disruption risks on manufacturer pricing decisions and expected profits should be taken into account when assessing supply disruption risks and market competition.

In this paper, we propose models to study two different procurement strategies adopted by competing manufacturers to mitigate supply disruption risks. We consider a two-echelon supply
chain that comprises two suppliers and two manufacturers. The manufacturers purchase products from suppliers and transform these intermediate products into differentiated final products, which are then sold in the market. One manufacturer uses an Emergency Procurement (EP) strategy and the other uses an Optimal Allocation Procurement (OAP) strategy. In the base model, one supplier is unreliable but less expensive and the other is perfectly reliable but more expensive. The manufacturer with the EP strategy can purchase products from the spot market and respond effectively to supply disruptions. The manufacturer with the OAP strategy allocates its purchases between both suppliers. The setting in the extension model resembles that in the base model except that the competing manufacturers face two unreliable suppliers. In both models, we examine how the procurement strategies affect manufacturers’ ordering decisions and expected profits under supply disruption risks and horizontal competition. This paper obtains some managerial insights. For example, the increasing underage cost implies the increasing possibility of using more reliable supply (reliable sole sourcing; dual sourcing with order inflation; diversification) for the manufacturer with the OAP strategy. Higher procurement cost decreases the possibility of using more reliable supply for the manufacturer with the OAP strategy. The OAP strategy to maximize manufacturer’ profit in a noncompetitive scenario does not necessarily yield competitive advantage for a manufacturer in a competitive scenario.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature. Section 3 then introduces and formulates the problem. The base model and extension model are then proposed in Sections 4 and 5, respectively. Section 6 provides numerical computations to develop further insights. Finally, Section 7 summarizes the conclusions and outlines future research topics.

2. Literature review

Supply uncertainty is generally characterized by three approaches. The first approach is the random yield model in which the quantity of units delivered by the supplier is a random fraction of the quantity ordered by the buyer (Babich, Ritchken, & Burnetas, 2007; Dada, Petruzzi, & Schwarz, 2007; Deo & Corbett, 2009; Gurnani & Gerchak, 2007; Yano & Lee, 1995). The second approach models the supply uncertainty as the “all-or-nothing” type called supply disruption. In this scenario, the supplier can deliver either the entire amount ordered or nothing (Li, Wang, & Cheng, 2010; Shou, Huang, & Li, 2009; Tang & Kouvelis, 2011; Tomlin, 2006; Wadecki, Babich, & Wu, 2012). The third approach models the supply uncertainty with a stochastic lead-time or a stochastic capacity (Babich, 2010). In this paper we use the Bernoulli yield (all-or-nothing) to model supplier status.

The related literature comprises two streams. The first stream discusses the procurement strategy for managing supply risks. Sourcing products from multiple suppliers such that a problem at one supplier does not affect the entire supply is called diversification. A diversification strategy can effectively reduce disruption risk but involves higher costs and complexity. Babich et al. (2007) and Dada et al. (2007) provide an in-depth discussion of this strategy. Having an emergency supplier who is not normally used, but can be activated in the event of a supply problem is called a backup strategy or contingent strategy. For example, in response to the air traffic disruption resulting from the September 11th terrorist attack, Chrysler temporarily turned to ground shipping to send components from the U.S. to their Dodge Ram assembly plant in Mexico (Tomlin, 2006). One advantage of a backup strategy is that it incurs costs only in the event of an actual disruption. Hou, Zeng, and Zhao (2010) study a use case strategy in which two substituted products are sourced from two suppliers. Kouvelis and Li (2012) study the potential use of two contingency strategies on top of the conventional time buffer to address lead-time uncertainty. Gurnani, Gümüs, Ray, and Ray (2012) investigate one buyer facing two suppliers under supply risk, and address the buyer’s optimal allocation procurement strategy under asymmetric information. Meena and Sarmah (2013) investigate an order allocation problem experienced by a manufacturer with multiple suppliers where there exists risks of supply disruption. They build a mixed integer nonlinear programming model that they solve using the genetic algorithm. Unlike the existing literature, which investigates a single buyer that employs a diversification strategy or backup strategy to manage supply disruption risks, our paper focuses on strategic interactions among buyers/manufacturers that occupy a competitive setting and commit to different procurement strategies.

The second stream of related literature details manufacturer/retailer competition under supply disruption risk. Shou et al. (2009) discussed competition between two supply chains, subject to supply uncertainty. Deo and Corbett (2009) build a two-stage model of a Cournot competition among several suppliers to investigate the effect of supply uncertainty on buyer entry and production strategies. Tang and Kouvelis (2011) investigate a dual-sourcing strategy by studying the benefits of supplier diversification for dual-procurement duopolists. Chen and Guo (2014) develop an analytical model to evaluate competing retailers’ sourcing strategies under supply uncertainty. They consider a common supplier that sells its uncertain supply. Our paper differs from the previous literature in several ways. First, we use a different setting to study manufacturers’ competitive behavior. Second, we consider the OAP and EP strategies for managing supply disruption risks, which were not investigated in the existing literature, using the game theoretic framework. Third, we jointly consider pricing and ordering decisions.

3. Model description and assumptions

We consider a two-echelon supply chain comprising two suppliers and two manufacturers. Both manufacturers replenish their stocks from upstream suppliers and compete in a market vulnerable to supply disruption risks. The two manufacturers provide differentiated products. The supply chain model is depicted in Fig. 1. The product has a short life cycle and is sold in a single selling season. One of the suppliers is perfectly reliable but expensive, while the other is unreliable but less expensive. This setting is generally used in the literature (Babich et al., 2007; Chen & Guo, 2014; Gurnani et al., 2012; Hou et al., 2010; Li et al., 2010; Serel, 2008; Tomlin, 2006). We assume that supplier 1 is perfectly reliable and there is some probability that supplier 2 may experience disruption. If supplier 2 is disrupted, it becomes unable to provide essential inputs for downstream manufacturers. The two manufacturers use distinctive procurement strategies to mitigate supply disruptions affecting the buyer’s main supplier. Lu, Huang, and Shen (2011) study a supply chain model in which two substituted products are sourced from two suppliers. Kouvelis and Li (2012) study the potential use of two contingency strategies on top of the conventional time buffer to address lead-time uncertainty. Gurnani, Gümüş, Ray, and Ray (2012) investigate one buyer facing two suppliers under supply risk, and address the buyer’s optimal allocation procurement strategy under asymmetric information. Meena and Sarmah (2013) investigate an order allocation problem experienced by a manufacturer with multiple suppliers where there exists risks of supply disruption. They build a mixed integer nonlinear programming model that they solve using the genetic algorithm. Unlike the existing literature, which investigates a single buyer that employs a diversification strategy or backup strategy to manage supply disruption risks, our paper focuses on strategic interactions among buyers/manufacturers that occupy a competitive setting and commit to different procurement strategies.

The second stream of related literature details manufacturer/retailer competition under supply disruption risk. Shou et al. (2009) discussed competition between two supply chains, subject to supply uncertainty. Deo and Corbett (2009) build a two-stage model of a Cournot competition among several suppliers to investigate the effect of supply uncertainty on buyer entry and production strategies. Tang and Kouvelis (2011) investigate a dual-sourcing strategy by studying the benefits of supplier diversification for dual-procurement duopolists. Chen and Guo (2014) develop an analytical model to evaluate competing retailers’ sourcing strategies under supply uncertainty. They consider a common supplier that sells its uncertain supply. Our paper differs from the previous literature in several ways. First, we use a different setting to study manufacturers’ competitive behavior. Second, we consider the OAP and EP strategies for managing supply disruption risks, which were not investigated in the existing literature, using the game theoretic framework. Third, we jointly consider pricing and ordering decisions.
disruption risks. Manufacturer A uses an OAP strategy, and procure from reliable supplier 1 and Q₂ from unreliable supplier 2. Meanwhile, manufacturer B utilizes an EP strategy. Specifically, it procure Q₁ from unreliable supplier 2 under normal circumstances, but in the event of disruption to supplier 2 will procure Q₂ from the spot market at a cost of c₂ per unit. We assume c₂ > c₁ > c₃, which is realistic. No capacity limit exists on either supplier. Manufacturer B’s procurement behavior is thus contingent on the realized state of supplier 2. The notation is shown in Table 1.

The sequence of events is illustrated in Fig. 2. First, manufacturer A and manufacturer B decide their retail prices (pₐ, pₕ) according to the wholesale price pair (c₁, c₂) charged by both suppliers. In anticipation of market demand, both manufacturers place their orders simultaneously. Manufacturer A places order Q₁ with supplier 1, and places order Q₂ with supplier 2. Manufacturer B places order Q₃ with supplier 2. Supplier 2 experiences disrupted with a probability of 1 − x, x ∈ (0, 1). Should disruption occur, manufacturer B procures Q_e from the spot market at a cost of c₃ per unit. Finally, the market partially clears based on the realized supply of products from the suppliers and the spot market. At this time, if the manufacturer cannot satisfy its demand, it will incur costs of c₄ per unit of demand. If the manufacturer has inventory remaining after fulfilling this demand, it will incur costs of c₄ per unit. We assume a price commitment that requires both manufacturers to determine their sale prices before the realization of supply and to maintain those prices throughout the selling season. This price commitment strategy is exemplified by Apple with its iPads. We assume both manufacturers are risk neutral and that information about cost, price, and reliability is common knowledge. We assume the market demand for manufacturer i, i = (A, B) to be d_i = a_i − p_i + p_b, 0 < b_i < 1, where a_i is the market scale and b_i is the substitutability coefficient of the two products. This type of demand function is common in both the economic and supply chain management literature. Huang, Leng, and Parlar (2013) provide an excellent review of this topic.

4. The base model

4.1. The ordering decision stage

In this section, we first characterize the expected profit functions for both manufacturers, then derive their optimal order quantities and prices. We compare the effects of the OAP strategy and the EP strategy on the expected profits for both manufacturers. The problem is solved by backward induction. Before formulating the objective functions for both manufacturers, we identify several conditions under which the optimal ordering quantities should satisfy both manufacturers.

**Lemma 1.** The optimal order quantity for manufacturer B should satisfy Q₁ ≤ dₐ and Q₂ ≤ dₐ. The optimal order quantity for manufacturer A should satisfy Q₁ + Q₂ ≥ dₐ and Q₂₁ ≤ dₐ.

**Table 1** List of notations.

| Q₁, Q₂ | Firm A’s order quantities from suppliers 1 and 2 respectively |
| Q₁, Q₂ | Firm B’s order quantities from supplier 2 and spot market respectively |
| c₁, c₂, c₃ | Unit procurement cost from supplier 1, supplier 2 and spot market respectively |
| pₐ, pₕ | Selling prices charged by Firm A and B respectively |
| c₄ | Unit short trage cost and unit holding cost respectively |
| dₐ, dₕ | Demands for firm A and B respectively |
| x | Reliability level of supplier 2 |

In the third stage, manufacturer B makes ordering decisions contingent on the state of supplier 2. If supplier 2 is disrupted, according to Lemma 1, manufacturer B procures Q₂ = dₕ from the spot market to maximize profit. The maximum profit for manufacturer B at this time is π₂ = (pₕ − c₅)Q₂. Otherwise, manufacturer B receives Q₁ = dₐ from supplier 2. In the second stage, both manufacturers place their orders simultaneously. Manufacturer A chooses Q₁ and Q₂ to maximize its expected profit. The optimization problem can be formulated as follows:

\[
\text{max } Q₁, Q₂: \piₐ = aₐ(pₐ \min (dₐ, Q₁ + Q₂) - c₁Q₁ - c₂Q₂ - c₃(Q₁ + Q₃) - c₄(dₐ - Q₃ - Q₂) + (1 - x)(pₐ \min (dₐ, Q₁) - c₁Q₁ - c₃(Q₁ - dₐ) - c₄(dₐ - Q₁) - c₅Q₂))
\]

s.t. \( Q₁ + Q₂ \geq dₐ \)

\( Q₁ \leq dₐ \)

After several algebraic operations, the objective function (1) can be simplified as follows:

\[
\text{max } Q₁, Q₂: \piₐ = aₐ(pₐdₐaₐ - c₁Q₁ - c₂Q₂ - c₃(Q₁ + Q₂) - dₐ) + (1 - x)(pₐQ₁ - c₁Q₁ - c₃(dₐ - Q₁))
\]

s.t. \( Q₁ + Q₂ \geq dₐ \)

\( Q₁ \leq dₐ \)

**Proposition 1** characterizes manufacturer A’s OAP strategy.

**Proposition 1.** The OAP strategy and order quantities for manufacturer A are given by:

\[
\begin{align*}
Q₁^* &= dₐ, Q₂^* = 0 & & \text{if } aₐ < aₐ^0 \\
Q₁^* &= 0, Q₂^* = dₐ & & \text{if } aₐ > aₐ^0
\end{align*}
\]

where \( aₐ^0 = \frac{pₐdₐaₐ}{pₐdₐaₐ + c₂} \) which is the reliability threshold value.

**Proof.** see Appendix A. \( \square \)

**Proposition 1** shows the structural property and order quantities for manufacturer A. The situation where \( Q₁^* > 0 \) and \( Q₂^* > 0 \) is called the diversification strategy, that where \((Q₁^*, Q₂^*) = (0, dₐ)\) or \((Q₁^*, Q₂^*) = (dₐ, 0)\) is called the single sourcing strategy, and that where \( Q₁^* > dₐ \) can be called order inflation. Order inflation is not optimal for manufacturer A in the base model. Notably, if c₁ equals c₃, manufacturer A always sources from supplier 1 with order quantity dₐ.

4.2. The pricing decision stage

In the second stage, manufacturer B procures Q₂ = dₕ to maximize expected profit. The maximum profit for manufacturer B is \( \pi₂ = pₕdₕ - c₅dₕ \). Looking forward from the first stage, the rational manufacturer A acts in the second stage following Proposition 1. Therefore, manufacturer A sets the selling price in the first stage to maximize expected profit. We analyze this in the following section.
4.2.1. Single sourcing with supplier 1

If manufacturer A anticipates placing an order \( Q_1^* = d_A \) with reliable supplier 1 in the second stage, then the expected profit function in the first stage can be expressed as follows:

\[
\max_{p_A} \pi_A^1 = (p_A - c_1)Q_1^* = (p_A - c_1)(a - p_A + \beta p_B)
\]  

Taking the derivative of (3) with respect to \( p_A \), manufacturer A’s response function is:

\[
p_A(p_B) = \frac{a - \beta p_B + c_1}{2}
\]

The profit function for manufacturer B can be expressed as follows:

\[
\max_{p_B} \pi_B^1 = (p_B - c_2)Q_1^* + (1 - \alpha)(p_B - c_2)Q_3^*
\]

Taking the derivative of (4) with respect to \( p_B \), the response function for manufacturer B is:

\[
p_B(p_A) = \frac{a + \beta p_A + \alpha c_2 - \alpha c_e}{2}
\]

After solving these two response functions, the following proposition is presented.

**Proposition 2.** If manufacturer A uses single sourcing with reliable supplier 1, the equilibrium prices for both manufacturers are:

\[
\begin{align*}
 p_A^* &= \frac{2a + \alpha c_2 + \alpha c_e - \alpha c_3}{4 - \alpha^2} \\
 p_B^* &= \frac{2a + \alpha c_2 - 2 \alpha c_e}{4 - \alpha^2}
\end{align*}
\]

where \( K = \alpha c_2 + (1 - \alpha)c_e \). The expected profits are as follows:

\[
\begin{align*}
\pi_A^* &= \frac{(2a + \alpha c_2 + \alpha c_e - \alpha c_3)^2}{4 - \alpha^2} \\
\pi_B^* &= \frac{(2a + \alpha c_2 - 2 \alpha c_e)^2}{4 - \alpha^2}
\end{align*}
\]

Note that the expressions of equilibrium prices are incomplete because \( p_A \) depends on the assumption that manufacturer A uses single sourcing with supplier 1, which in turn depends on whether the condition \( \alpha < \alpha_0 \) is satisfied. Furthermore, the value of \( \alpha_0 \) depends on \( p_A \). In Section 4.2.3, we propose an approach for calculating the equilibrium results.

**Corollary 1.** Suppose manufacturer A uses single sourcing with supplier 1. If \( K > c_1 \), the equilibrium price for manufacturer A is lower than that for manufacturer B and the expected profit for manufacturer A is larger than that for manufacturer B. That is, \( p_A^* > p_B^* \). Otherwise, the reverse holds. That is, \( p_A^* < p_B^* \). \( \pi_A^* > \pi_B^* \).

**Corollary 1** compares the equilibrium price and expected profit for manufacturers A and B.

4.2.2. Single sourcing with supplier 2

If manufacturer A places an order \( Q_2^* = d_A \) with unreliable supplier 2 in the second stage, it should choose \( p_A \) in the first stage to maximize expected profit, as follows:

\[
\max_{p_A} \pi_A^2 = (p_A - c_2)Q_2^* - (1 - \alpha)c_e d_A
\]

Substituting \( c_3 = p_B - c_2 \) into (6), then taking the derivative with respect to \( p_B \), the response function for manufacturer A is:

\[
p_A(p_B) = \frac{c_3 + p_B + c_e}{2}
\]

After solving these two response functions, the following proposition is presented.

**Proposition 3.** If manufacturer A uses single sourcing with unreliable supplier 2, the equilibrium prices for both manufacturers are as follows:

\[
\begin{align*}
 p_A^2 &= \frac{2a + \alpha K - 2 \alpha c_e + \alpha c_3}{4 - \alpha^2} \\
 p_B^2 &= \frac{2a + \alpha K + 2 \alpha c_e}{4 - \alpha^2}
\end{align*}
\]

where \( K = \alpha c_2 + (1 - \alpha)c_e \). The expected profits are:

\[
\begin{align*}
\pi_A^2 &= \frac{(2a + \alpha K - 2 \alpha c_e + \alpha c_3)^2}{4 - \alpha^2} \\
\pi_B^2 &= \frac{(2a + \alpha K + 2 \alpha c_e)^2}{4 - \alpha^2}
\end{align*}
\]

**Corollary 2.** If manufacturer A uses single sourcing with supplier 2, the equilibrium price for manufacturer A is lower than that for manufacturer B. That is, \( p_A^2 < p_B^2 \).

4.2.3. The approach for calculating the equilibrium results

Comparing Propositions 1 and 3, we get the following corollary.

**Corollary 3.** When manufacturer A uses single sourcing with supplier 1, the equilibrium price for manufacturer A is larger than that when manufacturer A uses single sourcing with supplier 2, that is, \( p_A^1 > p_A^2 \).

Because manufacturer A employs a specific procurement strategy in the second stage following **Proposition 1**, this strategy should be considered when setting the sales price in the first stage. To maintain consistency between the pricing decisions prerequisite and the procurement decision conditions, the corresponding equilibrium results can be calculated using the following procedures:

(1) Suppose manufacturer A uses single sourcing with supplier 1. Computing the sales price \( p_1^* \) following **Proposition 2** and substituting \( p_1^* \) into \( \alpha_0 = \frac{\alpha c_2 + \alpha c_e}{2} \), we obtain \( \alpha_0 (p_1^*) \).

(2) If \( \alpha < \alpha_0 (p_1^*) \), then manufacturer A should set the sales price to \( p_1^* \) in the first stage and use single sourcing with reliable supplier 1 in the second stage. Stop. If \( \alpha = \alpha_0 (p_1^*) \), manufacturer A can set the sales price to \( p_1^* \) in the first stage and employ the diversification strategy in the second stage. Stop. If \( \alpha > \alpha_0 (p_1^*) \), the prerequisite of calculating price \( p_1^* \) is inconsistent with the assumption in step (1). Go to the next step.

(3) Suppose manufacturer A uses single sourcing with supplier 2. Computing the sales price \( p_2^* \) following **Proposition 3** and substituting \( p_2^* \) into \( \alpha_0 = \frac{\alpha c_2 + \alpha c_e}{2} \), we obtain \( \alpha_0 (p_2^*) \).

(4) Following **Corollary 3**, we have \( p_1^* > p_2^* \), then \( \alpha_0 (p_1^*) > \alpha_0 (p_2^*) \). Therefore, \( \alpha > \alpha_0 (p_1^*) \) implies \( \alpha > \alpha_0 (p_2^*) \). According to **Proposition 1**, manufacturer A should set the sales price to \( p_2^* \) in the first stage and use single sourcing with unreliable supplier 2 in the second stage. Stop.

Using the above procedures, we can determine the equilibrium prices and payoffs for both manufacturers in the basic model.

4.3. Comparative analysis

We summarize comparative statics for the equilibrium prices and expected profits of both manufacturers with various parameters in Table 2. From columns 2, 3, 6, and 7, we observe that the
equilibrium prices for both manufacturers move in the same direction because the price competition is strategically complementary. From columns 4 and 5, we find the expected profits for both manufacturers are moving in opposite directions because manufacturers A and B use different suppliers. Therefore, if the parameters for one manufacturer turn “good”, the profit of its competitor will decrease. From columns 8 and 9, we observe that if manufacturer A uses single sourcing with unreliable supplier 2, the expected profits for both manufacturers decrease with \( c_1 \). Additionally, manufacturer A’s expected profit increases with \( c_1 \) and decreases with \( \alpha \), whereas manufacturer B’s expected profit decreases with \( c_1 \) and increases with \( \alpha \). The symbol “\( \cdots \)” denotes an independent relationship between the corresponding entries in the table.

**Corollary 4.** The reliability threshold value \( x_0 = \frac{p_A - c_2 + c_1}{p_A - c_1 + c_2} \) decreases with \( \alpha \) and the cost differentials, respectively, and increases with the underage cost \( c_u \).

**Proof.** From Table 2, we obtain \( \frac{\partial Q_1}{\partial \alpha} < 0, \frac{\partial p_A}{\partial \alpha} > 0, i = 1, 2, \text{then} \frac{\partial Q_1}{\partial \alpha} < 0, \text{let the cost differentials be } C_1 = c_1 - c_2, \text{then} \frac{\partial Q_1}{\partial \alpha} < 0 \text{ and } \frac{\partial Q_1}{\partial \alpha} > 0, \Box.

This corollary says that if the reliability of supplier 2 increases, the threshold value \( x_0 \) will decrease. Therefore, \( \alpha \) is likely larger than \( x_0 \), which makes manufacturer A increasingly likely to use unreliable supplier 2. If the understock cost increases, then so will too will the reliability threshold \( x_0 \). Consequently, \( \alpha \) is likely less than \( x_0 \), which increases the possibility of manufacturer A using perfectly reliable supplier 1. If the cost differentials increase, then supplier 2 has an increasing cost advantage over supplier 1 and manufacturer A becomes more likely to procure from supplier 2.

**5. The extension model**

**5.1. The ordering decision stage**

In the previous section, we showed that manufacturer A’s ordering behavior depends on the threshold value, which is related to supplier reliability level, under stock costs and the cost differentials between the two suppliers. If both suppliers are unreliable, will the threshold value remain unchanged? If not, what will its value be? What are the corresponding equilibrium outcomes in this scenario?

In this section, the two suppliers are unreliable and hence disruption is likely. To facilitate our analysis, throughout this section we assume the two suppliers are symmetric and have identical reliability \( \alpha \), \( \alpha \in (0, 1) \) and wholesale price \( c_2 \). The decisions timeline and parameters are identical to those in Section 3. For simplicity, the underage cost is assumed to equal the procurement cost: that is, \( c_u = c_2 \). Similar to Lemma 1, we present the following lemma for use in the subsequent analysis.

**Lemma 2.** The optimal order quantities for manufacturer B are \( Q_1^* = d_b \) and \( Q_2^* = d_b \). The optimal order quantities for manufacturer A satisfy \( Q_1^* + Q_2^* \geq d_b \). Manufacturer B’s decisions in the third stage are exactly as described in Section 4. The emergency order quantity \( Q_e^* = d_b \) is procured from the spot market to maximize profit in the event of disruption to supplier 2. Otherwise, manufacturer B receives order quantity \( Q_e^* = d_b \) from supplier 2.

We can express manufacturer A’s optimization problem in the second stage, as follows:

\[
P : \max_{Q_1, Q_2} p_A \times \left[ Q_1 (Q_1 - Q_2) - c_0 (Q_1 + Q_2 - d_b) \right]
\]

\[
+ \sum_{i=1}^{2} \alpha (1 - \alpha) \left[ Q_i \min (d_a, Q_i) - c_0 (Q_1 - Q_i) \right]
\]

\[
- c_0 (Q_i - d_b) \right) - (1 - \alpha) \right) c_u d_b
\]

s.t. \( Q_1 + Q_2 \geq d_b \)

The first term in the objective function denotes the expected profit when neither supply suffers disruption; the second term is the expected profit when one supplier suffers disruption and the other does not; the last term is the expected loss when both suppliers suffer disruption.

**Proposition 4.** The OAP strategy and ordering quantity for manufacturer A are given by:

\[
\begin{align*}
Q_1^* &= d_A, \quad Q_2^* = d_A \quad \text{if } \lambda > 0 \\
0 \leq Q_1^* \leq d_A, \quad Q_2^* = d_A \quad \text{if } \lambda = 0 \\
Q_1^* &= 0, \quad Q_2^* = d_A \quad \text{if } \lambda < 0
\end{align*}
\]

where \( \lambda = x^2 (c_2 - c_1) + \alpha (1 - \alpha) (p_a - c_2 + c_1) \).

Proof of Proposition 4 is similar to proof of Proposition 1. After several algebraic operations, the above expressions can be rewritten in the following form:

\[
\begin{align*}
Q_1^* &= d_A, \quad Q_2^* = d_A \quad \text{if } \lambda < \lambda_1 \\
0 \leq Q_1^* \leq d_A, \quad Q_2^* = d_A \quad \text{if } \lambda = \lambda_1 \\
Q_1^* &= 0, \quad Q_2^* = d_A \quad \text{if } \lambda > \lambda_1
\end{align*}
\]

where \( \lambda_1 = \frac{p_a + c_2 - c_1}{p_a + c_2 + c_1} \) and \( \lambda_1 \) is the reliability threshold value.

Proposition 4 shows the structural property and order quantities for manufacturer A. We call \( (Q_1^*, Q_2^*) = (d_A, d_A) \) dual sourcing. From proposition 4, we observe that order inflation may be optimal for manufacturer A when facing two unreliable suppliers. This observation differs from that in our basic model. Proposition 4 also demonstrates that if supplier reliability is relatively low, i.e., \( x < x_1 \), then manufacturer A should employ dual sourcing with order inflation to reduce supply disruption risk. Meanwhile, if supplier reliability is relatively high, i.e., \( x > x_1 \), manufacturer A does not need to employ a risk mitigation strategy. Manufacturer A can place an order of size \( d_b \) with either supplier. When supplier reliability equals the specific value \( x_1 \), sole sourcing and dual sourcing are equivalent options for manufacturer A. The total order quantities for manufacturer A can be expressed using a stepwise decreasing function of reliability \( x \). Proposition 4 demonstrates that the reliability threshold value \( x_1 = \frac{p_a + c_2 - c_1}{p_a + c_2 + c_1} \) influences manufacturer A’s procurement decisions.

**5.2. The pricing decision stage**

Looking forward from the first stage, the rational manufacturer A acts in the second stage following Proposition 4. Manufacturer A sets the sales price to \( p_A \) in the first stage to maximize expected profits.
5.2.1. Dual sourcing

In this scenario, manufacturer A places orders of size $Q_1 = d_a$ with supplier 1 and $Q_2 = d_a$ with supplier 2 in the second stage; therefore we can express manufacturer A’s expected profit function in the first stage as follows:

$$\max_{p_A} \pi_A = x^2(p_A d_a - 2c_A d_a - c_A d_a) + 2x(1-x)(p_A d_A - c_A d_A) - (1-x)^2 c_A d_A$$  \hspace{1cm} (7)

After substituting $c_0 = c_2, c_0 = p_A - c_2$ into (7) and taking the derivative with respect to $p_A$, we have $p_A(p_A) = \frac{a (1-x) + (1-4x) p_A}{2(2x^2 - 4x + 1)}$.

The payoff function for manufacturer B is identical to expression (4) and manufacturer B’s best response function is: $p_B(p_A) = \frac{a (1-x) + (1-4x) p_A}{2(2x^2 - 4x + 1)}$.

Solving the two response functions, we get the following proposition.

**Proposition 5.** If manufacturer A uses dual sourcing, the equilibrium prices for both manufacturers are as follows:

$$p^*_A = \frac{2a + \beta K - 2M + p_A}{4 - p_A}$$
$$p^*_B = \frac{2a - M + p_A}{4 - p_A}$$

where $K = x c_2 + (1-x) c_r, M = \frac{(1-4x) a}{2x^2 - 4x + 1}$. The expected profits are:

$$\pi^*_A = \frac{2a + \beta K - 2M + p_A}{4 - p_A}$$
$$\pi^*_B = \frac{2a - M + p_A}{4 - p_A}$$

where

$$T = 4x^2 a + 4x^2 M + 2x^2 \beta a + 2x^2 \beta K - 4x^2 c_2 + x^2 c_0^2 - 8xa - 8xM - 4x\beta a + 4x\beta K + 16xc_2 - 4xc_0^2 + 2a + 2M + \beta a + \beta K - 4c_2 + c_r^2 \beta^2$$

It is difficult to derive an explicit relationship between the expected profits for both manufacturers. We use numerical computations to illustrate the relationship in Section 6. The following corollary shows the relationship between the equilibrium prices for both manufacturers.

**Corollary 5.** Suppose manufacturer A uses dual sourcing. If $K > M$, the equilibrium price for manufacturer A is less than that for manufacturer B, that is, $p^*_A < p^*_B$; otherwise, the reverse holds, that is, $p^*_A > p^*_B$.

5.2.2. Sole sourcing

Without loss of generality, we assume that manufacturer A uses single sourcing with supplier 2 at the second stage. Manufacturer A chooses $p_2$ in the first stage to maximize expected profit. Therefore, this scenario is equivalent to Section 4.2.2. The objective functions for both manufacturers are identical to those in Section 4.2.2. Following a similar approach, we obtain the equilibrium prices and expected profits for both manufacturers based on Proposition 3 as follows:

$$p^*_2 = p^*_2, p^*_2 = p^*_2, \pi^*_A = \pi^*_A, \pi^*_B = \pi^*_B$$

The following corollary compares the equilibrium prices and profits for the manufacturers.

**Corollary 6.** If manufacturer A uses single sourcing with supplier 2, the equilibrium price for manufacturer A is lower than that for manufacturer B and the expected profit for manufacturer A is larger than that for manufacturer B. That is, $p^*_A < p^*_B, \pi^*_A > \pi^*_B$.

5.2.3. The approach for calculating the equilibrium results

Because the equilibrium prices $p^*_A$ and $p^*_B$ are nonlinear functions of reliability level $x$, it is difficult to derive the explicit relationship between $p^*_A$ and $p^*_B$. Because manufacturer A makes procurement decisions in the second stage according to Proposition 4, these decisions should be considered when setting the sales price in the first stage. To maintain consistency between the pricing decision prerequisites and the procurement decision conditions, the equilibrium results can be calculated using the following procedures:

1. Suppose manufacturer A uses dual sourcing from both suppliers. Calculating the sales price $p^*_A$ and substituting it into $x_1 = \frac{a_1 + c_0}{a_1 + c_0}$ we get $x_1 (p^*_A)$.
2. If $x < x_1 (p^*_A)$, manufacturer A should set the sales price to $p^*_A$ in the first stage and use dual sourcing in the second stage. Stop.
3. If $x > x_1 (p^*_A)$, manufacturer A may set the sales price to $p^*_A$ in the first stage and employ a diversification strategy in the second stage. Stop.
4. If $x > x_1 (p^*_B)$, the prerequisite of calculating price $p^*_B$ is inconsistent with the assumption in step (1). Go to the next step.
5. Calculating the sales price $p^*_B$ and substituting it into $x_2 = \frac{a_2 + c_0}{a_2 + c_0}$ we obtain $x_2 (p^*_B)$.
6. If $x < x_1 (p^*_B)$, no equilibrium pricing and sourcing decisions are made. Stop.

5.3. Comparative analysis

In Table 3, we summarize comparative statics for the equilibrium prices and expected profits for both manufacturers given various parameters. Because we have assumed that $c_1 = c_2, c_1$ is not listed in Table 3. Columns 6–9 are identical to the corresponding columns in Table 2. The symbol “+” denotes that no explicit relationship exists between the two corresponding entries in the table. This is because of the complex item $M$ in the equilibrium prices and the expected profits. Consequently, we use numerical computations to demonstrate these relationships.

**Corollary 7.** The reliability threshold value $x_1 = \frac{a_1 + c_0}{a_1 + c_0}$ increases with the understock cost $c_0$, and decreases with the overstock cost $c_r$ and unit procurement cost $c_2$, respectively.

From Corollary 7, we observe that if the understock cost $c_0$ increases, then the reliability threshold $x_1$ will increase. Therefore, $x$ is likely less than $x_1$, which makes manufacturer more likely to use dual sourcing to mitigate supply risks. Additionally, if overstock cost $c_r$ increases, then the reliability threshold $x_1$ will decrease. Therefore, $x$ is most likely larger than $x_1$, which increases the possibility of manufacturer A using a single sourcing strategy. If the unit procurement cost $c_2$ increases, then reliability threshold $x_1$ decreases. Therefore $x$ likely exceeds $x_1$ and manufacturer A will most likely use single sourcing.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Summary of comparative statics for both manufacturers in the extension model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\partial \pi^*_A / \partial a_1$</td>
<td>$&gt;0$</td>
</tr>
<tr>
<td>$\partial \pi^*_B / \partial a_2$</td>
<td>$&gt;0$</td>
</tr>
<tr>
<td>$\partial \pi^*_A / \partial c_0$</td>
<td>$&lt;0$</td>
</tr>
<tr>
<td>$\partial \pi^*_B / \partial c_r$</td>
<td>$&lt;0$</td>
</tr>
<tr>
<td>$\partial \pi^*_A / \partial c_2$</td>
<td>$&lt;0$</td>
</tr>
</tbody>
</table>
From the base model to the extension model, the total reliabilities of the suppliers are reduced, and the total quantities procured by manufacturer A increase for the given sales price. The results obtained from both models differ in the expressions of the threshold values. The threshold values are a proxy of the supplier reliabilities, which combines all the critical factors that influence manufacturer procurement decisions. Compared with the threshold value of \( x_0 = \frac{x + n - x}{m + c - x} \) in the base model, \( x_1 \) depends on the overstock cost \( c_s \) while \( x_0 \) is independent of \( c_s \). This is because the order inflation associated with the OAP strategy in the extension model may incur overstock costs. However, order inflation does not occur in the base model, so overstock costs are not incurred.

6. Numerical computation

In this section, we investigate the effect of the reliability \( \alpha \) on the threshold values, equilibrium prices and expected profits for both manufacturers in the base and extension models. We also show the effect of normal procurement cost \( c_2 \) and emergency procurement cost \( c_s \) on the expected profit for both manufacturers in the extension model. We consider the following basic parameters: \( \alpha = 50, c_1 = 5, c_2 = 3, c_s = 7, \beta = 0.5 \). We vary the values of \( \alpha \) within the range \((0,1)\) in increments steps of 0.01.

6.1. The effect of \( \alpha \) on the reliability threshold values

When \( \alpha \) varies, the values of thresholds \( x_0(\alpha) \) and \( x_1(\alpha) \) also vary. We define \( x_0^* \) as the turning point where \( x_0^* = \min \{x_0|\alpha < x_1\} \). Similarly, we define \( x_1^* \) where \( x_1^* = \min \{x_1|\alpha < x_1\} \). The upper panel of Fig. 3 displays the trajectory of \( x_0 \), which is a monotone decreasing function of \( \alpha \). When \( \alpha < x_0^* = 0.969 \), then \( \alpha < x_0(\alpha) \) holds. When \( \alpha \geq x_0^* \), then \( \alpha \geq x_0(\alpha) \) holds. The lower panel of Fig. 3 depicts the trajectory of \( x_1 \), which is not monotone function of \( \alpha \) as noted in Table 3. When \( \alpha < x_1^* = 0.922 \), then \( \alpha < x_1(\alpha) \) holds. When \( \alpha \geq x_1^* \), then \( \alpha \geq x_1(\alpha) \) holds. At the turning points, manufacturer A will alter its sourcing decision and the equilibrium prices for both manufacturers will change accordingly as displayed in Fig. 4.

6.2. The effect of \( \alpha \) on the equilibrium prices and expected profits

Using the procedures in Section 4.2.3, we compute the equilibrium prices and expected profits for both manufacturers in the base model. When the reliability of supplier 2 is less than 0.969, manufacturer A will use single sourcing with reliable supplier 1. Otherwise, manufacturer A will employ single sourcing with unreliable supplier 2. The upper panel of Fig. 4 illustrates that the equilibrium prices for both manufacturers are decreasing with \( \alpha \), as shown in Table 2. The relationship between the two price functions verifies corollaries 1 and 2. The lower panel of Fig. 4 depicts the expected profits for both manufacturers. When \( \alpha > 0.969 \), manufacturer A’s expected profit exceeds that of manufacturer B. When \( \alpha < 0.5 \), manufacturer A’s expected profit exceeds that of manufacturer B. When \( 0.5 < \alpha < 0.969 \), manufacturer B’s expected profit exceeds that of manufacturer A. These observations are also shown in Corollary 1.

Using the procedures in Section 5.2.3, we calculate the results from the extension model. When supplier reliability is less than 0.922, manufacturer A uses dual sourcing combined with order inflation. Otherwise, manufacturer A uses single sourcing with either supplier. The upper panel of Fig. 5 describes the equilibrium prices for both manufacturers. The lower panel of Fig. 5 describes the expected profits for both manufacturers. All trajectories are non-monotonic.

6.3. The effect of costs on expected profits

The effects of cost parameters on expected profits for both manufacturers in the base model are reported in Table 2. The effects of the cost parameters on expected profits in the extension model are presented to better understand the properties of these...
nonlinear functions. When we analyze one cost parameter, the others remain fixed. The cost parameters also satisfy our previous assumptions.

Fig. 6 plots the expected profit of manufacturer A with respect to reliability $\alpha$ and procurement cost $c_2$. The expected profit $\pi_{3A}^\alpha$ increases as $\alpha$ increases. The expected profit $\pi_{3A}^\alpha$ increases as $c_2$ increases when $\alpha < 0.3$ and decreases as $c_2$ increases when $\alpha \geq 0.3$ (see Table 4). Manufacturer A thus realizes negative profit when supplier reliability is low.

Fig. 7 plots the expected profit of manufacturer A with respect to reliability $\alpha$ and cost $c_e$. The expected profit $\pi_{3A}^\alpha$ increases as $\alpha$ increases. The expected profit $\pi_{3A}^\alpha$ decreases as $c_e$ increases when $\alpha < 0.3$ and increases as $c_e$ increases when $\alpha \geq 0.3$ (see Table 4). Manufacturer A also realizes negative profit when the reliabilities are low.

Fig. 8 plots the expected profit of manufacturer B with respect to reliability $\alpha$ and cost $c_2$. The expected profit $\pi_{3B}^\alpha$ is not monotonic.

### Table 4

<table>
<thead>
<tr>
<th>$c_2$</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>659.36</td>
<td>605.36</td>
<td>641.43</td>
<td>632.56</td>
<td>623.76</td>
<td>615.96</td>
<td>608.16</td>
<td>600.36</td>
<td>592.56</td>
</tr>
<tr>
<td>4.0</td>
<td>659.36</td>
<td>605.36</td>
<td>641.43</td>
<td>632.56</td>
<td>623.76</td>
<td>615.96</td>
<td>608.16</td>
<td>600.36</td>
<td>592.56</td>
</tr>
<tr>
<td>4.5</td>
<td>659.36</td>
<td>605.36</td>
<td>641.43</td>
<td>632.56</td>
<td>623.76</td>
<td>615.96</td>
<td>608.16</td>
<td>600.36</td>
<td>592.56</td>
</tr>
<tr>
<td>5.0</td>
<td>659.36</td>
<td>605.36</td>
<td>641.43</td>
<td>632.56</td>
<td>623.76</td>
<td>615.96</td>
<td>608.16</td>
<td>600.36</td>
<td>592.56</td>
</tr>
<tr>
<td>5.5</td>
<td>659.36</td>
<td>605.36</td>
<td>641.43</td>
<td>632.56</td>
<td>623.76</td>
<td>615.96</td>
<td>608.16</td>
<td>600.36</td>
<td>592.56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$c_e$</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
<th>7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>625.46</td>
<td>615.96</td>
<td>606.46</td>
<td>596.96</td>
<td>587.46</td>
<td>577.96</td>
<td>568.46</td>
<td>558.96</td>
<td>549.46</td>
</tr>
<tr>
<td>6.0</td>
<td>625.46</td>
<td>615.96</td>
<td>606.46</td>
<td>596.96</td>
<td>587.46</td>
<td>577.96</td>
<td>568.46</td>
<td>558.96</td>
<td>549.46</td>
</tr>
<tr>
<td>6.5</td>
<td>625.46</td>
<td>615.96</td>
<td>606.46</td>
<td>596.96</td>
<td>587.46</td>
<td>577.96</td>
<td>568.46</td>
<td>558.96</td>
<td>549.46</td>
</tr>
<tr>
<td>7.0</td>
<td>625.46</td>
<td>615.96</td>
<td>606.46</td>
<td>596.96</td>
<td>587.46</td>
<td>577.96</td>
<td>568.46</td>
<td>558.96</td>
<td>549.46</td>
</tr>
<tr>
<td>7.5</td>
<td>625.46</td>
<td>615.96</td>
<td>606.46</td>
<td>596.96</td>
<td>587.46</td>
<td>577.96</td>
<td>568.46</td>
<td>558.96</td>
<td>549.46</td>
</tr>
</tbody>
</table>
increases when \( c_1 \) decreases as \( a \) increases (see Table 5).

Table 5

<table>
<thead>
<tr>
<th>( a )</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( c_3 )</th>
<th>( c_4 )</th>
<th>( c_5 )</th>
<th>( c_6 )</th>
<th>( c_7 )</th>
<th>( c_8 )</th>
<th>( c_9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3.5</td>
<td>941.36</td>
<td>944.13</td>
<td>1240.68</td>
<td>1006.16</td>
<td>1012.30</td>
<td>1024.48</td>
<td>1039.06</td>
<td>1055.53</td>
</tr>
<tr>
<td>0.2</td>
<td>4.0</td>
<td>943.89</td>
<td>944.19</td>
<td>1283.07</td>
<td>1009.30</td>
<td>1013.36</td>
<td>1024.30</td>
<td>1037.96</td>
<td>1053.78</td>
</tr>
<tr>
<td>0.3</td>
<td>4.5</td>
<td>946.42</td>
<td>944.25</td>
<td>1326.17</td>
<td>1012.45</td>
<td>1014.42</td>
<td>1024.13</td>
<td>1036.87</td>
<td>1052.02</td>
</tr>
<tr>
<td>0.4</td>
<td>5.0</td>
<td>948.96</td>
<td>944.30</td>
<td>1369.99</td>
<td>1015.61</td>
<td>1015.48</td>
<td>1023.95</td>
<td>1035.77</td>
<td>1050.25</td>
</tr>
<tr>
<td>0.5</td>
<td>5.5</td>
<td>951.50</td>
<td>944.36</td>
<td>1414.51</td>
<td>1018.75</td>
<td>1016.53</td>
<td>1027.77</td>
<td>1034.68</td>
<td>1048.48</td>
</tr>
<tr>
<td>0.6</td>
<td>5.9</td>
<td>952.12</td>
<td>944.37</td>
<td>1414.52</td>
<td>1018.76</td>
<td>1016.52</td>
<td>1027.76</td>
<td>1034.65</td>
<td>1048.47</td>
</tr>
<tr>
<td>0.7</td>
<td>6.0</td>
<td>953.74</td>
<td>944.38</td>
<td>1414.53</td>
<td>1018.77</td>
<td>1016.51</td>
<td>1027.75</td>
<td>1034.64</td>
<td>1048.46</td>
</tr>
<tr>
<td>0.8</td>
<td>6.5</td>
<td>958.17</td>
<td>944.43</td>
<td>1414.58</td>
<td>1018.82</td>
<td>1016.49</td>
<td>1027.72</td>
<td>1034.61</td>
<td>1048.42</td>
</tr>
<tr>
<td>0.9</td>
<td>7.0</td>
<td>962.60</td>
<td>944.48</td>
<td>1414.63</td>
<td>1018.87</td>
<td>1016.46</td>
<td>1027.69</td>
<td>1034.57</td>
<td>1048.39</td>
</tr>
</tbody>
</table>

Fig. 9. Expected profit of manufacturer B versus \( \alpha \) and \( c_\alpha \).

with reliability \( \alpha \), but peaks at \( \alpha = 0.3 \). The expected profit \( p_B^2 \) increases as \( c_2 \) increases when \( a < 0.5 \) and decreases as \( c_2 \) increases when \( a > 0.5 \) (see Table 5).

Fig. 9 illustrates the expected profit of manufacturer B with respect to reliability \( \alpha \) and cost \( c_\alpha \). The expected profit \( p_B^2 \) is not monotonic with reliability \( \alpha \) but peaks at \( \alpha = 0.3 \). The expected profit \( p_B^2 \) decreases as \( c_\alpha \) increases (see Table 5).

7. Conclusions

The EP and the OAP strategies are two appealing and popular approaches for managing supply disruption risks. In this paper, we develop two analytic models to study procurement strategies of competing manufacturers under supply disruption risks. We investigate how procurement strategies will affect two manufacturers engaging in price competition and also propose approaches for calculating the equilibrium prices to characterize manufacturers’ ordering and pricing decisions of competing manufacturers; (3) proposing solution procedures to calculate the equilibrium prices and profits; (4) finding that procurement decisions depend on supplier’s reliability, sales price, underage cost and cost differentials between suppliers; (5) developing insights regarding the OAP and EP strategies, i.e., the optimal procurement strategy that maximizes profit for a manufacturer in a non-competitive scenario does not necessarily produce a competitive advantage in a competitive scenario; under a wide range of parameters, the EP strategy can yield larger profit for the manufacturer than the OAP strategy when suppliers are all unreliable.

This paper contributes to the existing literature by achieving the following: (1) investigating two competitive manufacturers employing different procurement strategies in the presence of supply disruption risks; (2) building competitive models to analyze the ordering and pricing decisions of competing manufacturers; (3) proposing solution procedures to calculate the equilibrium prices and profits; (4) finding that procurement decisions depend on supplier’s reliability, sales price, underage cost and cost differentials between suppliers; (5) developing insights regarding the OAP and EP strategies, i.e., the optimal procurement strategy that maximizes profit for a manufacturer in a non-competitive scenario does not necessarily produce a competitive advantage in a competitive scenario; under a wide range of parameters, the EP strategy can yield larger profit for the manufacturer than the OAP strategy when suppliers are all unreliable.

This paper contributes to the existing literature by achieving the following: (1) investigating two competitive manufacturers employing different procurement strategies in the presence of supply disruption risks; (2) building competitive models to analyze the ordering and pricing decisions of competing manufacturers; (3) proposing solution procedures to calculate the equilibrium prices and profits; (4) finding that procurement decisions depend on supplier’s reliability, sales price, underage cost and cost differentials between suppliers; (5) developing insights regarding the OAP and EP strategies, i.e., the optimal procurement strategy that maximizes profit for a manufacturer in a non-competitive scenario does not necessarily produce a competitive advantage in a competitive scenario; under a wide range of parameters, the EP strategy can yield larger profit for the manufacturer than the OAP strategy when suppliers are all unreliable.

The model framework can be extended in future as follows. First, the effects of capacity limitations on suppliers should be considered. This issue is of practical importance and worth investigating. Second, it might be worthwhile to study the effects of different supply uncertainties, such as an unreliable supplier that delivers a negative profit. The EP strategy outperforms the OAP strategy except when supplier reliability is extremely high.

(4) The OAP strategy, which maximizes profit in a non-competitive environment, as pointed out in Gurnani et al. (2012), may not generate competitive advantage in a competitive environment. Therefore, the manufacturer should carefully examine the OAP strategy (including the diversification strategy, dual sourcing strategy and order inflation strategy) in a competitive scenario.

(5) A higher underage cost increases the likelihood of the manufacturer adopting the OAP strategy using more reliable supply (reliable sole sourcing; dual sourcing with order inflation; diversification). Higher procurement cost decreases the possibility of using more reliable supply for the manufacturer adopting the OAP strategy.

Acknowledgments

This work is partially supported by the National Natural Science Foundation of China (NSFC) under Grants 71001111 and 71161004. The authors thank the anonymous referees for their constructive comments leading to the improvement of this paper.
Appendix A

Proof of Proposition 1. To solve the constrained optimization problem, we introduce the Lagrange multiplier \( \lambda \geq 0 \) and \( \mu \geq 0 \), then the relaxed function can be written as

\[ L_\lambda = \pi_A + \lambda(Q_1 + Q_2 - d_A) + \mu(d_A - Q_1). \]

The KKT conditions of which are:

\[
\frac{\partial L_\lambda}{\partial Q_1} = (1 - \lambda)(p_A + c_o) - c_1 - \lambda c_o + \lambda - \mu \leq 0 \quad (A1)
\]

\[
\frac{\partial L_\lambda}{\partial Q_2} = -\lambda(c_2 + c_o) + \lambda \leq 0 \quad (A2)
\]

\[ Q_1 \frac{\partial L_\lambda}{\partial Q_1} = 0 \quad (A3) \]

\[ Q_2 \frac{\partial L_\lambda}{\partial Q_2} = 0 \quad (A4) \]

\[ \lambda(Q_1 + Q_2 - d_A) = 0 \quad (A5) \]

\[ \mu(d_A - Q_1) = 0 \quad (A6) \]

\[ Q_1 + Q_2 - d_A \geq 0 \quad (A7) \]

\[ d_A - Q_1 \geq 0 \quad (A8) \]

\[ \lambda \geq 0, \mu \geq 0 \quad (A9) \]

For exposition brevity, let \( \delta = (1 - \lambda)(p_A + c_o) - c_1 - \lambda c_o \)

**Case 1** When \( \lambda = 0 \) and \( \mu = 0 \). From \( (A2) \) and \( (A4) \), we obtain \( Q_3 = 0 \).

Subcase 1 If \( \delta < 0 \), from \( (A3) \), we have \( Q_3 = 0 \), which contradict with \( (A7) \) and \( (A8) \), so this case cannot occur.

Subcase 2 If \( \delta = 0 \), we have \( Q_3 = d_A \).

Subcase 3 If \( \delta > 0 \), then \( (A1) \) is not valid, this case cannot occur.

**Case 2** When \( \lambda > 0 \) and \( \mu > 0 \). From \( (A5) \) and \( (A6) \), we obtain \( Q_1 = d_A, Q_2 = 0 \).

**Case 3** When \( \lambda = 0 \) and \( \mu > 0 \). From \( (A6) \), we obtain \( Q_1 = d_A \). From \( (A3) \) and \( (A1) \), we have \( \delta - \mu = 0 \). Since \( \mu > 0 \), which requires \( \delta > 0 \) holds. From \( (A2) \) and \( (A4) \), we obtain \( Q_2 = 0 \).

**Case 4** When \( \lambda > 0 \) and \( \mu = 0 \). Then we get \( \delta < 0 \). From \( (A5) \), we have \( Q_1 + Q_2 = d_A \). The solution is \( Q_1^* = d_A, Q_2^* = d_A - \delta, 0 \leq \delta < d_A \).

Subcase 1 If \( (Q_1 = 0, Q_2 = d_A) \), from \( (A2) \) and \( (A4) \), we have \( \lambda = 0 \). From \( (A1) \) we have \( \delta < 0 \), combining the previous equality and inequality, the parameters must satisfy \( \delta > \lambda(c_2 + c_o) \).

Subcase 2 If \( (Q_1 = d_A, Q_2 = 0) \), from \( (A1) \), we have \( \delta + \lambda = 0 \). From \( (A2) \), we get \( -\lambda(c_2 + c_o) < \lambda \leq 0 \). Combining the previous equality and inequality, the parameters must satisfy \( \delta > \lambda(c_2 + c_o) \).

Subcase 3 If \( (Q_1 = d_A, Q_2 = d_A - \delta, 0 < \delta < d_A) \), from \( (A1)-(A4) \), we obtain \( \lambda = \lambda(c_2 + c_o)\) and \( \delta + \lambda = 0 \). Combining the two equalities, the parameters must satisfy \( \delta + \lambda(c_2 + c_o) = 0 \).

We summarize the previous results in the following table.

<table>
<thead>
<tr>
<th>( \delta )</th>
<th>( \delta + \lambda(c_2 + c_o) )</th>
<th>( \pi_A ) - ( \lambda(c_2 + c_o) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta &lt; 0 )</td>
<td>( Q_1^* = d_A, Q_2^* = 0 )</td>
<td>( Q_1 = d_A, Q_2 = 0 )</td>
</tr>
<tr>
<td>( \delta = 0 )</td>
<td>( Q_1^* = d_A, Q_2^* = 0 )</td>
<td>( Q_1 = d_A, Q_2 = 0 )</td>
</tr>
<tr>
<td>( \delta &gt; 0 )</td>
<td>( Q_1^* = d_A, Q_2^* = 0 )</td>
<td>( Q_1 = d_A, Q_2 = 0 )</td>
</tr>
</tbody>
</table>

Let \( \alpha = \frac{\delta + \lambda(c_2 + c_o)}{\lambda(c_2 + c_o)} \), we can further summarize these results into three cases:

- \( \alpha < \alpha_0 \), \( \alpha = \alpha_0 \), \( \alpha > \alpha_0 \), which is more straightforward and demonstrated in the Proposition 1.

References


