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Research Article

Dual-Source Procurement Strategies of Emergency Materials Considering Risk Attitudes

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The uncertainty of emergencies makes the emergency procurement face many risks, so the risk management is particularly important of the emergency procurement. The risk attitude of decision makers will significantly affect the decision-making of risk management. In this paper, the risk management problem with different risk attitudes of emergency procurement consisting of dual-source suppliers and the single government is studied, and a government-led Stackelberg game is used to analyze the risks of each link to establish an emergency procurement model under the option contract, and the optimal decision-making is obtained. The effects of reserve period, risk avoidance coefficient, and probability of emergency on optimal decision-making are analyzed with different risk attitude. Moreover, we investigate the coordination of the government-led supply chain coordination under the risk aversion and risk-neutral conditions of emergency supply chain participants. The results show that the model can control the risk while reducing the cost of government procurement and ensuring the revenue of suppliers. Finally, the influence of each parameter on the optimization decision is verified by a numerical example.

1. Introduction

Due to the fact that sudden accidents such as earthquakes, floods, snowstorms, epidemic, and terrorist attacks have dramatically happened. These sudden accidents often result in sudden changes in demand for emergency materials over a short period of time, which can increase the risk of supply chain disruptions. In case of sudden accidents, people's production and life will suffer serious losses if the emergency materials cannot be delivered in time. For instance, in 2011, the earthquake, tsunami, and nuclear crisis in Japan severely affected the supply of Toyota vehicles, resulting in a huge loss, and the extreme storm weather in northern Finland has caused widespread power outages posing a serious supply risk [1–3]. In 2019, the power supply was disrupted by the Australia fire, costing 76 million dollars loss [4]. In 2020, the COVID-19 outbreak has directly led to an acute shortage in the area of medical supplies such as masks, goggles, and protective clothing [5, 6]. In 2021, the global natural disaster situation was complex with extreme disaster events occurring frequently, for instant, Haiti was hit by a 7.3 magnitude earthquake, glaciers broke off in northern India, which eventually led to serious loss of life and property [7]. In 2022, the conflict between Russia and Ukraine impacted on global food supply chains, triggered a refugee crisis, and caused a severe economic downturn [8]. In the face of sudden accidents, it is necessary to quickly supply sufficient materials to minimize the risk of emergency procurement, under these circumstances, the government emergency materials reserve will directly affect the speed of emergency response [9]. Although the government reserves of emergency materials in advance can reduce the shortage risk, the impairment of reserve materials is affected by factors such as storage time and characteristics of raw materials [10]. Therefore, while ensuring sufficient emergency materials reserve, how to determine the optimal amount of emergency materials reserve, reduce emergency materials waste, and avoid the problem of overdue emergency materials occupying inventory has become a new challenge for government organizations to purchase and store emergency materials. As a result, based on the option contract, many scholars have established an emergency procurement model considering the reserve period, so as to optimize the emergency materials reserve mechanism [11–14].

As an important part of emergency resource management, the procurement of emergency materials has a significant impact on the effectiveness of emergency rescue. At the reserve moment of emergency materials, the government purchases some emergency materials for storage at a certain price and signs an option contract at the same time [15]. When a disaster occurs, if the government's emergency material reserves are insufficient, the government will give priority to accepting social donations. If still insufficient, the government will compare the option strike price with the spot market price to select suitable suppliers [16–19]. Due to the unpredictable timing and severity of emergencies, the procurement of materials is faced with the risk of supply interruption [20–22]. In order to reduce supply interruptions and improve the reliability of the supply chain, the government can get supply replenished from a secondary source (spot market or a backup supplier), probably at a higher price. So, dual-source supply is widely used in the actual procurement. There are many research studies on dual-source procurement based on the supplier's reliability and cost [23–25], such as the optimal ordering problem for manufacturers to purchase parts from two suppliers who may have supply interruption under the condition of uncertain demand [26]. Multicycle dual-source procurement problems involve options and spot markets [27]. This research is mainly related to establishing a dual-source procurement model to include expensive reliable suppliers and cheap unreliable suppliers [28–30].

Sudden events also lead to changes in the risk attitudes of supply chain participants, from risk neutral to risk aversion. The study found that different risk aversions of participants in emergency material procurement have a great impact on the performance of the entire supply chain system. In the past, some scholars established newsvendor models in risk aversion to reduce the uncertainty of the emergency procurement risk management. There have been many research studies on the procurement of risk-neutral emergency materials [31]. However, it is rare to introduce the risk attitude of decision makers into the emergency procurement [32–34]. Due to the economic downturn in recent years, the risk aversion has attracted the attention of many scholars. For instance, companies are making decisions in a risk-averse environment amid the instability of the dollar and turmoil caused by the trade war [35]. In reality, in order to reduce the emergency procurement risk of supply interruption, it is feasible to introduce the decision makers' attitude to the risk of emergency procurement. With the expansion in research, some scholars conducted quantitative research on risks. Some of the earliest scholars used mean-variance to measure risks. However, the drawbacks of using this method for measuring risks have become increasingly apparent, and, as a result, some scholars proposed using the value at risk (VaR) in economics to measure risks. Some scholars considered that VaR measures the risk that has certain limitations, so VaR is improved for the conditional risk at value (CVaR) to measure the supply chain risk. CVaR is widely used as a common method to measure risk in the field of risk measurement [36]. At different confidence levels [37], CVaR is used to study emergency procurement strategies [38, 39]. Moreover, the supply chain coordination in both supplier-led and retailer-led supply chains with risk preference are explored under CVaR criterion [40–45].

In order to effectively reduce the risk of emergency procurement, better purchase emergency materials, improve the risk management ability of emergency procurement, we, in this paper, will realize the optimal the emergency procurement and the coordination of the emergency supply chain of the government-led with option contract under the condition of considering the risk attitude of participants.

2. Problem Description and Notation

2.1. Problem Description. We consider that an emergency procurement supply chain consists of a single government and two suppliers in which supplier 1 is a reliable contract supplier with low risk, supplier 2 is a risky supplier with a higher risk in the spot market that provides the government with emergency materials with no difference in quality. Due to the fact that demand for emergency materials is highly uncertain, the government emergency materials management department can order in two stages including the reserve stage and the emergency order stage. This emergency procurement problem constitutes a government-led Stackelberg game.

Before an emergency occurs, the government should determine how many emergency materials to reserve by considering historical data and propose an option contract as well. The government takes place procurement with a specified quantity of emergency materials to be delivered at a certain time. For this, the supplier 1 decides whether to accept the option contract or not according to the conditions given by the government and the actual situation. If supplier 1 accepts the option contract, the supplier 1 will ensure that the ordered goods with the specified unit price be delivered in the event of an emergency. The supplier 1, by no means, is not allowed to breach the contract. If the emergency materials price rises on the spot market in the event of an emergency, the government can buy the emergency materials based on the contract to save the cost, since the supplier 1 is not allowed to change the product price even though the market price rises.

In the aftermath of an emergency, the government will quickly transport the emergency materials to the disaster-stricken areas. If the government has enough reserves to meet emergency materials, it does not need to order addition. Without enough reserves, the government can accept social donations. If the emergency materials stored by the government and donated by the community still cannot meet the needs, the government consider whether to trigger the option contract or order from supplier 2 in the spot market. If the spot market price of the required emergency materials is higher than the purchase price in the contract, the government will use the contract. If the spot market price of emergency materials is lower than the purchase price in the contract. The government will buy all of the emergency materials from the supplier 2 in spot markets instead of executing the contract. But due to the impact of distance and policies, the supply chain of supplier 2 is at risk of interruption. It is assumed that the probability of interruption of supplier 2 is $r\,(0 < r < 1)$. The remaining needs for emergency materials demand unmet will lead to shortage cost, see Figure 1.

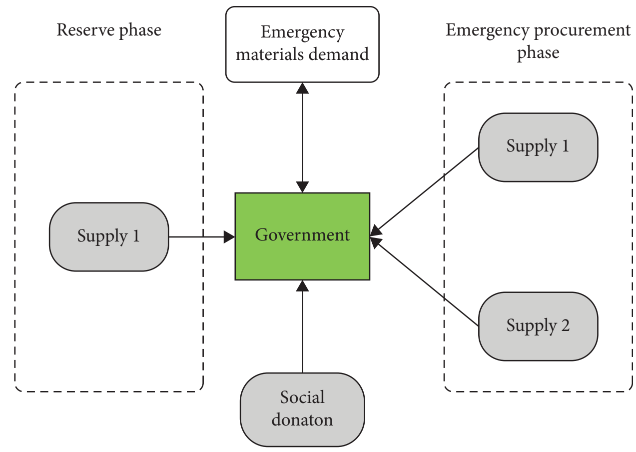

Figure 1: Pictorial representation of the emergency procurement.

2.2. Assumptions. For the concerned model, we further make the following assumptions:

Assumption 1. The delivery time of the purchase is zero and the transportation cost of emergency materials is also zero

Assumption 2. The risk attitude of reliable supplier 1 is risk neutral and the government is risk averse

Assumption 3. Before and after an sudden accident occurs, the government has only one procurement opportunity

Assumption 4. According to the past historical data, the probability density function $f(D)$ and cumulative distribution function $F(D)$ of the demand D for emergency materials are in line with the IFR increasing law and we can assumed that the maximum demand is U

2.3. Parameter Symbols Description. The symbols in the model are summarized as shown in Table 1.

3. Model Setting and Solution

Before an emergency occurs, the government can decide to buy q_1 units emergency materials at p_1 from supplier 1 for stockpiling and sign an option contract. The government places an order with a q units of emergency materials to be delivered, and the government sign an option to the supplier 1. If the supplier 1 accepts the option contract, he will provide q units of emergency materials to the government. Once an emergency occurs, the government will quickly transport the emergency materials to the disaster-stricken areas. If $0 < D \leq q_1$, the government does not need to order additional emergency materials. If $q_1 < D \leq q_1 + S$, the demand for emergency materials cannot be met, the government can accept social donations. If $q_1 + S < D \leq q_1 + q_2 + S$, according to the disaster situation, the government compares to the supplier 1 which buys q unit at the option exercise price p and the risk supplier 2 which buy q_2 units with the price p_2 in the spot market and selects the appropriate supplier. If $D \geq q_1 + q_2 + S$, the quantity of emergency supplies orders cannot satisfy the demand, it will cause serious losses and out-of-stock costs. If the ordered quantity of emergency materials is higher than the demand, it is necessary to carry out residual value treatment of the remaining emergency materials.

When emergency supply chain participants face the risk of supply disruption, due to the differences in the size, cultural concept, and upstream and downstream distribution, different participants entities in the emergency supply chain may have different attitudes and decisions on risk issue. Therefore, this paper analyzes the decision-making of the government and suppliers in the emergency supply chain under different risk attitudes.

3.1. All Participants in Supply Chain Hold a Risk-Neutral Attitude

3.1.1. The Optimal Decision of Risk-Neutral Suppliers. In the Stackelberg game, the government occupies the first-mover advantage, but on the game decision-making mechanism of both sides of the supply chain needs to start from the suppliers first, and then discuss the decision-making of the government backwards. Let's start by analyzing the supplier 1 as the sole source of emergency procurement to maximize its own interests, the expected profit of supplier 1 can be expressed as follows:

$$\Pi_1(q_1, q) = (p_1 - c_1)q_1 - (hT - o + c_1)q + (1-\mu)vq + \mu\left(\int_0^{q_1} vqf(D)dD + \int_{q_1}^{q_1+q} (1-\rho k)p(D-q_1) + v(q_1+q-D)f(D)dD + \int_{q_1+q}^{U} (1-\rho k)pqf(D)\mathrm{d}D\right), \quad (1)$$

Table 1: Parameter symbols description.

Symbol	Description
p_1	Long-term cooperative unit costs signed with supplier 1
p_2	Unit spot price with supplier 2
p	Unit option strike price
o	Unit option price
c_1	Unit production cost
h	Unit inventory cost
v	Unit residual value processing price
w	unit cost of shortage
q_1	The number of orders supplier 1 needs to provide to the government during the reserve period
q_2	The spot market orders with supplier 2
q	The contractual reserves of supplier 1
q_0	The systems orders quantity
${}^b q$	The spot market orders of both supplier 1 and supplier 2 are used as emergency procurement sources
${}^b q_2$	The contractual reserves of both supplier 1 and supplier 2 are used as emergency procurement sources
S	The amount of donations the government receives from society
T	Duration of material reserve period
D	Demand for emergency supplies
Π_1	The expected profit of supplier 1
Π_2	The expected profit of supplier 2
Π_3	The expected profit of supplier 1 and supplier 2
C_1	The government procurement costs of emergency supplies before an emergency occurs
C_2	The government procurement costs of emergency supplies after an emergency occurs
C	The government procurement total costs for emergency supplies
C_0	The systems procurement costs
μ	The probability of an emergency
ρ	The probability that the option strike price is higher than the spot market price
k	The probability that the government can obtain all the emergency supplies it needs on the spot market
η	The degree of government risk aversion
φ	The value at risk of the government under a certain degree of risk aversion

where the first term is the supplier 1's the reserve phase, inventory costs, and the profits of option contracts in the absence of emergencies, the second term is the sum of profit and cost when a disaster occurs. The first-order and the second-order derivatives of $\Pi_1(q_1, q)$ with respect to q are

$$\frac{\partial \Pi_1(q_1, q)}{\partial q} = o - hT - c_1 + \mu((1-\rho k)p - v)(1 - F(q_1 + q)),$$
$$\frac{\partial^2 \Pi_1(q_1, q)}{\partial q^2} = -\mu((1-\rho k)p - v) f(q_1 + q). \tag{2}$$

Owing to $f(q_1 + q) > 0$, we have $\partial^2 \Pi_1 / \partial q^2 < 0$. So $\Pi_1(q_1, q)$ is convex in q. We obtain the optimal reserve quantity of supplies 1

$$q^* = F^{-1}\left(1 - \frac{hT - o + c_1 - v}{\mu((1-\rho k)p - v)}\right) - q_1. \tag{3}$$

Next, the supplier 2 as the sole source of emergency procurement to maximize its own interests, the expected profits of supplier 2 can be expressed as follows:

$$\pi_2(q_2) = (1-r)\rho k(p_2 - c_2)q_2. \tag{4}$$

Since the expected profit function is linear, there is obviously no optimal solution.

Then, we introduce that both supplier 1 and supplier 2 are used as emergency procurement sources at the same time, the expected profits of suppliers are as follows:

$$\begin{aligned}\Pi_3\left(q_1, {}^b q_2, {}^b q\right) = {} & (p_1 - c_1)q_1 - (hT - o)^b q + (1-\mu)v^b q \\ & + \mu\left(\int_0^{q_1} v^b q f(D)dD + \int_{q_1}^{q_1 + {}^b q} (1-\rho k) r (p - c_1)(D - q_1) + v\left(q_1 + {}^b q - D\right) f(D)dD\right. \\ & + \int_{q_1}^{q_1 + {}^b q_2} (1-r)\rho k(p_2 - c_1)(D - q_1) + v\left(q_1 + {}^b q_2 - D\right) f(D)dD + \int_{q_1 + {}^b q}^{U} (1-\rho k) r^b q f(D)dD \\ & \left. + \int_{q_1 + {}^b q_2}^{U} (1-r)\rho k^b q_2 f(D)dD\right),\end{aligned} \tag{5}$$

where the first term is the suppliers' profits in the reserve phase, the second term is the sum of profit with sufficient reserve when an emergency occurs, the third term is the suppliers' profits during the emergency supplies procurement phase, the last term is shortage cost. According to the first-order and the second-order derivatives of $\Pi_3(q_1, {}^bq_2, {}^bq)$ with respect to q, q_1, we can get the suppliers optional decision

$$b\overrightarrow{q}^* = F^{-1}\left(\frac{o - hT + v + \mu(1-\rho k)r}{\mu r(1-\rho k)(1-p-c_1)}\right) - q_1, \tag{6}$$

$$b\overrightarrow{q}_2^* = F^{-1}\left(\frac{1}{1-p_2+c_2}\right) - q_1. \tag{7}$$

Proposition 1. *The optimal option reserve amount of supplier 1 decreases with the reserve period and increases with the option strike price, and the spot market optimal orders with supplier 2 has nothing to do with the reserve period and the option strike price.*

Proof. Please see Appendix.

From Proposition 1, we can get $\partial N/\partial T < 0, \partial N/\partial p > 0$, so N decrease with the T, N increase with the p and owing to $F^{-1}(D)$ is monotonically increasing, we have $\overrightarrow{q}^*$ decreases with T and increases with p. □

3.1.2. The Optimal Decision of Risk-Neutral Government. The government as the leader in the Stackelberg game reversely deduces the optimal procurement strategy based on the supplier's decision. In the reserve stage, the government orders from the supplier 1 and an option contract is signed. The government's input is limited to minimize losses that expected cost function of the reserve stage as follows:

$$C_1(q_1, q) = p_1 q_1 + hTq_1 + oq - vq_1. \tag{8}$$

When a sudden accident occurs, the government will use the reserved emergency materials for disaster relief work. If $q_1 \le D \le q_1 + S$, it needs to accept social donations. If $D \ge q_1 + S$, the government needs to choose between implement the option contract and spot market purchases, the government's expected cost function in the emergency procurement phase can be obtained as follows:

$$\begin{aligned} C_2(q_1, q_2, q) = {} & -v(q_1 - D)\int_0^{q_1} f(D)dD + \int_{q_1}^{q_1+q}(1-\rho k)pr(D-q_1)f(D)dD \\ & + \int_{q_1}^{q_1+q_2}(1-r)\rho k p_2 r(D-q_1)f(D)dD + \int_{q_1+q}^{U}(1-\rho k)prqf(D)dD + \int_{q_1+q_2}^{U}(1-r)\rho k p_2 q_2 f(D)dD \\ & + \int_{q_1+q+S}^{U}(1-\rho k)rwq(D-q_1-q-S)f(D)dD + \int_{q_1+q_2+S}^{U}(1-r)\rho kwq(D-q_1-q_2-S)f(D)dD, \end{aligned} \tag{9}$$

where the first term is the government's income for residual value treatment with emergency supplies are surplus, the second term is the government's cost of having insufficient reserves for emergency procurement, the third term is shortage cost.

The total expected cost of the government in the whole process of emergency procurement can be formulated as follows:

$$\begin{aligned} C(q_1, q_2, q) = {} & p_1 q_1 + hTq_1 + oq - (1-\mu)vq_1 + \mu\bigg(-v(q_1 - D)\int_0^{q_1} f(D)dD + \int_{q_1}^{q_1+q}(1-\rho k)pr(D-q_1)f(D)dD \\ & + \int_{q_1}^{q_1+q_2}(1-r)\rho k p_2(D-q_1)f(D)dD + \int_{q_1+q}^{U}(1-\rho k)prqf(D)dD + \int_{q_1+q_2}^{U}(1-r)\rho k q_2 f(D)dD\bigg) \\ & + \int_{q_1+q+S}^{U}(1-\rho k)rw(D-q_1-q-S)f(D)dD + \int_{q_1+q_2+S}^{U}(1-r)\rho kw(D-q_1-q_2-S)f(D)dD, \end{aligned} \tag{10}$$

where the first term is the cost of the reserve phase, the second term is the government's income for residual value treatment with emergency supplies are surplus, the third term is the government's cost of having insufficient reserves for emergency procurement, and the last term is the shortage cost. From the definition of supply chain coordination, when $q_1 + q^* = q_0/q_1 + q_2^* = q_0$, the coordination of the emergency supply will be achieved. By substituting $q_1 + q^* = q_0/q_1 + q_2^* = q_0$ into (10), we get the expression of the governments expected cost

$$
\begin{aligned}
C\left(q_1, q_2, q^*\right) = {} & p_1 q_1 + hTq_1 + oq^* - (1-\mu)vq_1 \\
& + \mu\Bigg(-v\left(q_1 - D\right)\int_0^{q_1} f(D)dD + \int_{q_1}^{q_1+q^*}(1-\rho k)pr\left(D-q_1\right)f(D)dD + \int_{q_1}^{q_1+q^*}(1-\rho k)pr\left(D-q_1\right)f(D)dD \\
& + \int_{q_1}^{q_1+q_2^*}(1-r)\rho kp_2 r\left(D-q_1\right)f(D)dD + \int_{q_1+q^*}^{U}(1-\rho k)prq^* f(D)dD + \int_{q_1+q_2^*}^{U}(1-r)\rho kq_2 f(D)dD\Bigg) \\
& + \int_{q_1+q^*+S}^{U}(1-\rho k)rwq^*\left(D-q_1-q^*-S\right)f(D)dD + \int_{q_1+q_2^*+S}^{U}(1-r)\rho kwq\left(D-q_1-q_2^*-S\right)f(D)dD.
\end{aligned}
\tag{11}
$$

When the government is risk-neutral, the optimal reserve amount of the government is obtained. The first-order and the second-order derivatives of $C\left(q_1, q_2, q^*\right)$ with respect to q_1 are

$$
\begin{aligned}
\frac{\partial C\left(q_1, q_2, q^*\right)}{\partial q_1} &= p_1 + hT - v - \mu v\left(1 - F\left(q_1\right)\right) - \mu\left((1-r)\rho kp_2 + r(1-\rho k)p\right)F\left(q_1\right), \\
\frac{\partial^2 C\left(q_1, q_2, q^*\right)}{\partial q_1^2} &= \mu v f\left(q_1\right) - \mu\left((1-r)\rho kp_2 + r(1-\rho k)p\right)f\left(q_1\right).
\end{aligned}
\tag{12}
$$

Obviously, we have $\partial^2 C\left(q_1, q_2, q^*\right)/\partial q_1^2 > 0$. So $C\left(q_1, q_2, q^*\right)$ is convex in q_1. The government's optimal reserve quantity of emergency material

$$
\overrightarrow{q_1^*} = F^{-1}\left(\frac{p_1 + hT - v - \mu v}{\mu\left((1-r)\rho kp_2 + r(1-\rho k)p\right) - \mu v}\right). \tag{13}
$$

3.1.3. The Coordination for Emergency Procurement Supply Chain Take a Risk-Neutral Attitude. In the government-led Stackelberg game, the government determining the amount of reserves before the occurrence of sudden accidents, and at the same time, signing option contracts with supplier 1 to determine option reserves, option prices, and option strike prices, so as to maximize profits by coordinating suppliers. To achieve emergency supply chain coordination, we consider a centralized emergency supply chain system composed of risk-neutral suppliers and the government. Now, our goal is to determine the optimal reserve quantity to maximize the profit of the entire supply chain system. Therefore, the expected profit of the emergency supply chain system is

$$
\begin{aligned}
C_0\left(q_0\right) = {} & \left(c_1 + hT\right)q_0 - (1-\mu)vq_0 \\
& + \mu\left(-\int_0^{q_1} v\left(q_0 - D\right)f(D)dD + \int_{q_0+S}^{U}\left((1-\rho k)pr + \rho kp_2(1-r)\right)\left(D - q_0 - S\right)f(D)dD\right),
\end{aligned}
\tag{14}
$$

where the first term is the cost of the reserve phase, the second term is the income of the emergency supply chain system for residual value treatment with emergency supplies are surplus, the third term is the cost of the emergency supply chain system having insufficient reserves for emergency procurement. The first-order and the second-order derivatives of $C_0\left(q_0\right)$ with respect to q_0 are

$$
\begin{aligned}
\frac{\partial C_0\left(q_0\right)}{\partial q_0} &= c_1 + hT - v - \mu\left(v\left(1 - F\left(q_0\right)\right)\right) \\
&\quad - \left((1-\rho k)pr + \rho kp_2(1-r)\right)\left(1 - F\left(q_0 + S\right)\right), \\
\frac{\partial^2 C_0\left(q_0\right)}{\partial q_0^2} &= \frac{\mu\left((1-\rho k)pr + \rho kp_2(1-r) - v\right)}{U}.
\end{aligned}
\tag{15}
$$

For the sake of calculation, we assume that demand follows a uniform distribution. Obviously, we have $\partial^2 C_0(q_0)/\partial q_0^2 > 0$. So $C_0(q_0)$ is convex in q_0. By solving (16), we can get the optimal reserve quantity of the emergency supply chain system with centralized decision making under the condition of risk-neutral is as follows:

$$q_0^* = U - \frac{U(c_1 + hT - v) + \mu S(1-\rho k)pr + \rho k p_2(1-r)}{\mu((1-\rho k)pr + \rho k p_2(1-r) - v)}. \quad (16)$$

In the case that both government and suppliers are risk-neutral when the optimal order quantity under decentralized decision mode is equal to the optimal order quantity under centralized decision mode, namely, $\overrightarrow{q_1^*} + \overrightarrow{q^*} = q_0^*$. The emergency supply chain reaches coordination again.

Proposition 2. *The emergency supply chain coordination which constitutes of risk-neutral suppliers and the government can be achieved when* $\overrightarrow{o} = hT - ((1-\rho k)p - v)(U(c_1 + hT - v) + \mu S(\rho k p_2(1-r)))/U(1-\rho k)pr + \rho k p_2(1-r)$.

Proof. Please see Appendix.

When both the government and the supplier are risk neutral, the coordination of the emergency supply chain can be realized when the option strike price reaches a certain level. □

3.2. Some Participants in the Emergency Supply Chain Take a Risk-Averse Attitude

3.2.1. The Optimal Decision of Risk-Averse Suppliers. Due to the risk of loss in the replenishment cycle, the suppliers have some preference when making decisions. To characterize the behavior preference of the suppliers, we adopt the CVaR theory. The CVaR criterion can be seen as a downsize risk criterion which focus more on the loss exceeding a given target level, or in other words, the benefit not satisfying a given target level. So, the CVaR model is established as follows:

$$\mathrm{VaR}_\eta(\pi_3(q_1, {}^bq_2, b_q)) = \sup(\varphi \in R | \Pr(\pi_3(q_1, {}^bq_2, b_q) \geq \varphi) \geq \eta), \quad (17)$$

where $\Pr(\pi_3(q_1, {}^bq_2, b_q) \geq \varphi)$ indicates the probability of the benefit $\pi_3(q_1, {}^bq_2, b_q)$ above value φ, and $VaR_\eta(\pi_3(q_1, {}^bq_2, b_q))$ means the maximum benefit of the suppliers who has been set risk-averse at the confidence level η. Using $\mathrm{VaR}_\eta(\pi_3(q_1, {}^bq_2, b_q))$ to denote the targeted benefit, the CVaR about benefit $\pi_3(q_1, {}^bq_2, b_q)$ going to the suppliers can now be defined as follows:

$$\mathrm{CVaR}_\eta(\pi_3(q_1, {}^bq_2, b_q)) = \frac{1}{\eta} E(\pi_3(q_1, {}^bq_2, b_q) \mid \pi_3(q_1, {}^bq_2, b_q) \leq \mathrm{VaR}_\eta(\pi_3(q_1, {}^bq_2, {}^bq))). \quad (18)$$

By maximizing this CVaR criterion to solve the optimization problem

$$\max \mathrm{CVaR}_\eta(\pi_3(q_1, {}^bq_2, b_q)) = \frac{1}{\eta} E(\pi_3(q_1, {}^bq_2, b_q) | \pi_3(q_1, {}^bq_2, b_q) \leq \mathrm{VaR}_\eta(\pi_3(q_1, {}^bq_2, b_q))), \quad (19)$$

It can also be rewritten as follows:

$$\mathrm{CVaR}_\eta(\pi_3(q_1, {}^bq_2, b_q)) = \max\left\{\varphi - \frac{1}{\eta}\left(E(\varphi - \pi_3(q_1, {}^bq_2, b_q))^+\right)\right\}. \quad (20)$$

Since the above problem is very complex, we convert it into an equivalent optimization problem as follows:

$$g(\pi_3(q_1, {}^bq_2, b_q)) = \varphi - \frac{1}{\eta}\left(E(\varphi - \pi_3(q_1, {}^bq_2, b_q))^+\right). \quad (21)$$

According to the above definition of CVaR, the objective function of the emergency material procurement decision model for risk-averse suppliers can be written as follows:

$$\begin{aligned} g(\pi_3(q_1, {}^bq_2, b_q)) &= \varphi - \frac{1}{\eta}\left(E(\varphi - \pi_3(q_1, {}^bq_2, b_q))^+\right) = \varphi - \frac{1}{\eta}\varphi \\ &- (p_1 - c_1)q_1 + (hT - o)^b q - (1-\mu)v^b q \\ &- \mu\left(\int_0^{q_1} v^b q f(D)dD + \int_{q_1}^{q_1+{}^bq} (1-\rho k)r(p-c_1)(D-q_1) + v(q_1 + {}^bq - D)f(D)dD\right. \\ &+ \left(\int_{q_1}^{q_1+{}^bq_2} (1-r)\rho k(p_2 - c_1)(D-q_1) + v(q_1 + {}^bq_2 - D)f(D)dD\right. \\ &\left.\left. + \int_{q_1+{}^bq}^{U} (1-\rho k)r^b q p f(D)dD + \int_{q_1+{}^bq_2}^{U} (1-r)\rho k^b q_2 p_2 f(D)dD\right)^+\right), \end{aligned} \quad (22)$$

where the first term is the CVaR of the reserve phase, the second term is the suppliers' CVaR for residual value treatment with emergency supplies are surplus, the third term is the suppliers' CVaR of having insufficient reserves for emergency procurement, the last term is the CVaR in shortage.

Proposition 3. *The optimal reserve of risk-averse supplier 1 and supplier 2 are*

$$ {}^{b}q^{*} = F^{-1}\left(\frac{\eta\left(hT - o + (1-\rho k)\left(p - c_{1}\right)\right)}{v - (1-\rho k)\left(p - c_{1}\right)r}\right) - q_{1}, \tag{23} $$

$$ {}^{b}q_{2}^{*} = F^{-1}\left(\frac{\eta\left(hT - o + (1-r)\rho k\left(p_{2} - c_{2}\right)\right)}{v - (1-r)\left(p - c_{1}\right)\rho k}\right) - q_{1}. \tag{24} $$

Proof. Please see Appendix.

When the suppliers are risk averse, the optimal amount of reserves is influenced by the value at risk. Through the above-given discussion, we can obtain the optimal reserve situation of the suppliers under different value at risk conditions. □

3.2.2. The Optimal Decision of Risk-Averse Government. Assuming this situation, supplier 1 and supplier 2 hold a neutral attitude towards the risk of supply disruption. Facing uncertain market demand, the government hopes to have stable procurement channels, reduce the probability of interruption risk, and take a risk-averse attitude. Due to the risk of supply disruption in the emergency procurement, the government tends to have some preference in making decisions. In order to characterize the risk preferences of the government, we introduce the CVaR theory in the emergency procurement. The CVaR model based on the expected cost function is actually to solve the cost mean larger than a certain quantile. The government does not control the part of cost lower than the quantile and only takes the value of the part higher than the cost as the decision-making target, the CVaR model is established as follows:

$$ \mathrm{CVaR}_{\eta}\left(C\left(q_{1}, q_{2}, q\right)\right) = \min\left\{\varphi + \frac{1}{1-\eta}\left[E\left(C\left(q_{1}, q_{2}, q\right) - \varphi\right)^{+}\right]\right\}. \tag{25} $$

Since the above-given problem is very complex, we convert it into an equivalent optimization problem as follows:

$$ g\left(C\left(q_{1}, q_{2}, q\right)\right) = \varphi + \frac{1}{1-\eta}\left[E\left(C\left(q_{1}, q_{2}, q\right) - \varphi\right)^{+}\right]. \tag{26} $$

According to the definition of supply chain coordination, the objective function of the risk-averse government decision-making model for emergency supplies procurement can be written as follows:

$$ \begin{aligned} g\left(C\left(q_{1}, q_{2}, q^{*}\right)\right) = {} & \varphi + \frac{1}{1-\eta}\left[E\left(C\left(q_{1}, q_{2}, q^{*}\right) - \varphi\right)^{+}\right] = \varphi \\ & + \frac{1}{1-\eta} p_{1} q_{1} + hT q_{1} + o q^{*} - (1-\mu) v q_{1} + \mu \int_{0}^{q_{1}} \left(-v\left(D - q_{1}\right) - \varphi\right)^{+} f(D) dD \\ & + \int_{q_{1}}^{q_{1}+q_{2}} \left((1-r)\rho k p_{2}\left(D - q_{1}\right) - \varphi\right)^{+} f(D) dD + \int_{q_{1}}^{q_{1}+q^{*}} \left((1-\rho k) p\left(D - q^{*}\right) - \varphi\right)^{+} f(D) dD \\ & + \int_{q_{1}+q^{*}}^{U} \left(\left((1-r)\rho k p_{2} q_{2} + (1-\rho k) r p q^{*} - \varphi\right)^{+} f(D) dD\right) + \int_{q_{1}+q^{*}+S}^{U} (1-\rho k) r w\left(D - q_{1} - q^{*} - S\right) - \varphi^{+} f(D) dD \\ & + \int_{q_{1}+q_{2}+S}^{U} \left(\left((1-r)\rho k w\left(D - q_{1} - q_{2} - S\right) - \varphi\right)^{+} f(D) dD\right), \end{aligned} \tag{27} $$

where the first term is the CVaR of the reserve phase, the second term is the government's CVaR for residual value treatment with emergency supplies are surplus, the third term is the government's CVaR of having insufficient reserves for emergency procurement, the last term is the CVaR in shortage.

Proposition 4. *When the government is risk averse, the optimal amount of reserves is influenced by the value at risk. The government's optimal reserve in this case is*

$$ q_{1}^{*} = F^{-1}\left(\frac{(1-\mu)v - (1-\eta)\left(p_{1} + hT\right)}{\mu r(1-\rho k) p}\right). \tag{28} $$

Proof. Please see Appendix.

The optimal reserve quantity of the government under risk aversion is consistent with the optimal reserve quantity of the supplier and is also related to the value at risk. By discussing different values at risk, the optimal reserve quantity of the government is obtained. □

Proposition 5. *The risk-averse government's optimal reserve decreases with the reserve period, increases with the risk aversion coefficient and increases with the probability of emergencies.*

Proof. Please see Appendix.

For the rest of the following discussing, we define $I = (1-\mu)v - (1-\eta)(p_{1} + hT)/\mu r(1-\rho k)p$, and we need to use the first-order derivative of I with respect to T, η, μ that we can get Proposition 5. □

3.2.3. The Coordination for Emergency Procurement Supply Chain Take a Risk-Averse Attitude. We derive the condition which the emergency supply chain consisting of the risk-averse government and the risk-neutral suppliers under the CVaR criterion. Since the suppliers and the government follow different risk preferences, we cannot use traditional risk-neutral supply chain coordination conditions. Instead, we introduce the conditions of supply chain coordination in which the supply chain agents have a risk preference. The supply chain is composed of risk-neutral suppliers and risk-averse governments, if (1) each agents individual rationality or participation conditions are satisfied, (2) the governments CVaR criterion is maximized, (3) the integrated supply chains expected profit is maximized. According to these three conditions, we derive the condition in which the government-led emergency supply chain coordination is achieved. The government should make sure that its order size is $q_1^* \geq q_0^*$, and the suppliers' reserve need to satisfy ${}^b q^* = q_1^*$.

Proposition 6. *The emergency supply chain coordination which constitutes of risk-averse suppliers and governments can be achieved when* $o^* = hT - v - \mu(1-\rho k)r + 2((p_1 + hT - V - \mu v)(\mu r(1-\rho k)(1-p_1-c_1))/\mu((1-\rho k)pr + \rho k p_2(1-r) - v))$, $p^* \leq U(\rho k p_2(1-r)(\mu S - 1))/U(\mu r(1-\rho k)(1+\mu S))$.

Proof. Please see Appendix.

Through the above derivation, it can be concluded that the conditions for coordination between the government and suppliers under risk aversion are as described above.

In the same way, we derive the coordination condition which the emergency supply chain consisting of the risk-averse suppliers and the risk-neutral government and consisting of the suppliers and the government are risk-averse under CVaR criterion. Because the derivation method is consistent, do not repeat here. □

4. Numerical Experiments

In this section, we deduce the optimal decision of urgent material purchase and analyze the influence of each parameter on it. Firstly, we present numerical experiments to better understand the influences of the parameters on optimal emergency procurement strategy. We assume that the model where there is the emergency materials demand D which obeys the uniform distribution in $[0, 3000]$, and other basic parameters are as follows: $p_1 = 20$, $p = 30$, $p_2 = 25$, $o = 5$, $c_1 = 10$, $c_2 = 15$, $h = 5$, $\mu = 0.2$, $k = 0.6$, $\rho = 0.2$, $w = 40$, $v = 5$. Furthermore, the parameter relationships should hold for the changes of parameters, including $p_1 > v$, $c_1 < p_1$, $c_2 < p_2$, $\rho \in [0,1]$, $k \in [0,1]$, $\mu \in [0,1]$. The numerical experiments result on procurement of emergency materials is listed in Figures 2–4.

In the following, we make a sensitivity analysis of some parameters that affect the optimal reserve quantity under emergency materials procurement. By Figure 2, it is evident that the optimal reserve of risk-neutral suppliers is negatively correlated with the reserve period and positively correlated with the occurrence probability of emergencies, and the impact

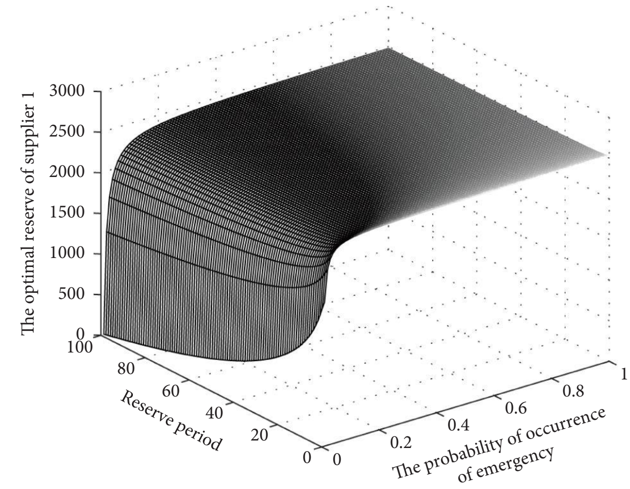

FIGURE 2: The influence of the probability of emergency occurrence and the reserve period on the optimal reserve amount of supplier 1.

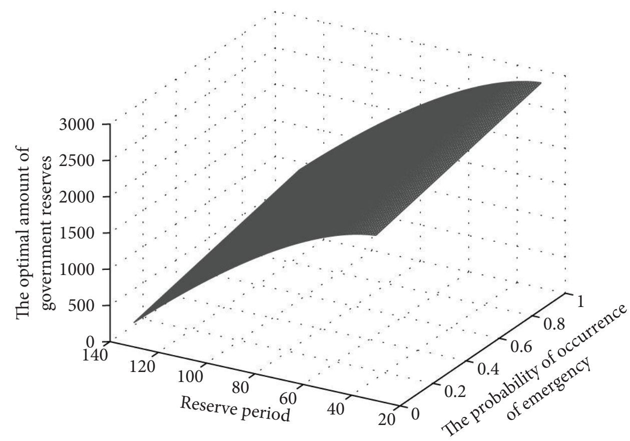

FIGURE 3: The influence of the probability of emergency occurrence and reserve period on the optimal government reserve.

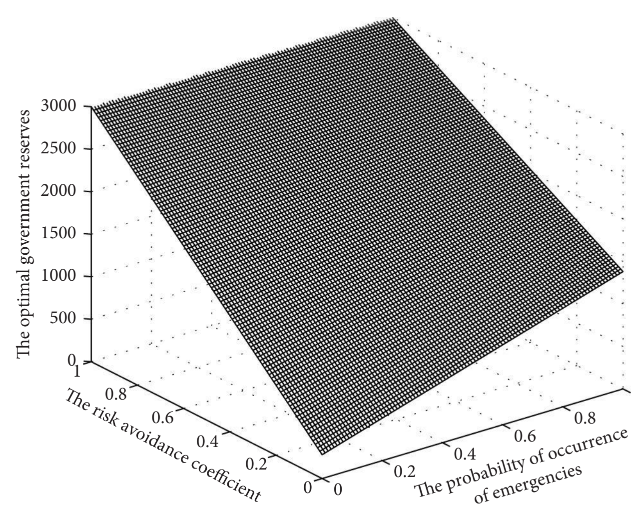

FIGURE 4: The influence of the probability of occurrence of emergencies and risk avoidance coefficient on optimal government reserves.

of the reserve period on the optimal reserve of suppliers gradually decreases, which means too long reserve period will cause a large amount of resource waste, reasonable selection of reserve time is more conducive to suppliers to obtain greater profits. By Figure 3, for the risk-averse government, it can be seen that when the probability of emergencies increases, so does the optimal reserve, and when the reserve period becomes longer, the optimal reserve amount decreases. From this, if the government wants to reduce emergency procurement costs, it will select the appropriate purchase time based on historical emergency data. In conclusion, both the risk-averse government and the risk-neutral supplier 1 can change the profit value by controlling the reserve period. By Figure 4, there is a positive linear relationship between the government's risk avoidance coefficient and the optimal reserve amount, and we can also see a rise in the optimal reserve amount with the probability of occurrence of emergency, indicating that the government's risk aversion degree has a larger influence on the reserve amount, which means that signing option contracts to reduce the degree of risk aversion is crucial for the government to control the cost of emergency procurement.

5. Conclusions

In this paper, we consider the risk management of the procurement of emergency supplies where decision makers have different risk attitudes, which is composed of the government and dual-source suppliers under the option contract. We establish a profit function that the suppliers and the government are risk-neutral, and then the optimal decisions of the government and suppliers under different risk attitudes are analyzed. According to CVaR, the CVaR functions of the government and suppliers under risk aversion are established to minimize the risk at the lowest cost, and the optimal reserves of the government and suppliers under different risk attitudes are obtained. Moreover, we investigate the coordination of emergency supply chains with risk preference. The impact analysis of contingency probability, reserve period, and risk aversion coefficient on the optimal reserve is also analyzed with the main conclusions as follows: under the option contract, the risk-neutral supplier's optimal reserves decrease with the reserve period and increase with the option strike price. The risk-averse government's optimal reserve decreases with the reserve period, increases with the risk aversion coefficient, and increases with the probability of emergencies. Finally, the conditions of supply chain coordination when the emergency supply chain members are risk-neutral and risk-averse are derived.

This research also has such disadvantages. First, the emergency procurement considered only a single government and dual-supplies. Thus, in future research, we can extend it to multiple supplies. Second, the suppliers in this paper is only emergency supplies with the government but in the actual process of emergency procurement, suppliers also consider other business value, so future research can analyze it.

Appendix

Proof of Proposition A.1. We assume $N = o - hT + v + \mu(1 - \rho k)pr/\mu(1-\rho k)r(1-p-c_1)$, the derivative of N with respect to T and p are

$$\begin{aligned}\frac{\partial N}{\partial T} &= \frac{-h}{\mu(1-\rho k)r(1-p-c_1)},\\ \frac{\partial N}{\partial p} &= \frac{(o - hT + v + \mu 1 - \rho k r 1 - \rho k)}{\mu\left((1-\rho k r t 1 - p - c_1)\right)^2}.\end{aligned} \tag{A.1}$$

Obviously, we can get $\partial N/\partial T < 0$, $\partial N/\partial p > 0$, so N decrease with the T, N increase with the p and owing to $F^{-1}(D)$ is monotonically increasing, we have $\overrightarrow{q^*}$ decreases with T and increases with p. □

Proof of Proposition A.2. From (6) and (13), we can obtain $\overrightarrow{q_1^*} + \overrightarrow{q^*} = U(o - hT + v + \mu(1-\rho k)r/\mu((1-\rho k)r- (1-\rho k)(p-c_1)r))$ and $q_0^* = U - U(c_1 + hT - v) + \mu S(1-\rho k)pr + \rho k p_2(1-r)/\mu((1-\rho k)pr + \rho k p_2(1-r) - v)$.

By solving $\overrightarrow{q_1^*} + \overrightarrow{q^*} = q_0^*$, we get

$$\begin{aligned}\overrightarrow{o} &= hT - v - (1-\rho k)(p-c_1)r\\ &\cdot\left(1 - \frac{U(c_1 + hT - v) + \mu S((1-\rho k)pr + \rho k p_2(1-r))}{U\mu((1-\rho k)pr + \rho k p_2(1-r) - v)}\right).\end{aligned} \tag{A.2}$$

□

Proof of Proposition A.3. The following derivation is similar to the solution of the optimal reserves of the risk-averse suppliers, and the concise derivation is as follows: □

Case A.1. $\varphi < (p_1 - c_1)q_1 - (hT-o)^b q + \mu v q$, in this case, given (19), we can obtain $g(\pi_3(q_1, {}^b q_2, b_q)) \equiv \varphi$. The first-order derivatives of $g(\pi_3(q_1, {}^b q_2, b_q))$ with φ, respect to $\varphi \equiv 1$, we have the risk-averse supplier 1's expected profit decrease with the value at risk.

Case A.2. $\varphi \geq (p_1 - c_1)q_1 - (hT-o)^b q + \mu v^b q$, $\varphi < (p_1 - c_1) q_1 - \mu(hT - o + (1-\rho k)r)(p-c_1)^b q$, we have $\alpha_1 = (p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k)r)(p-c_1)^b q - \varphi/\mu v < q$. If and only if the suppliers' order quantity is $(0, \alpha_1)$, we get

$$\begin{aligned}g\left(\pi_3\left(q_1, {}^b q_2, b_q\right)\right) &= \varphi - \frac{1}{\eta}((1-\mu)vq) + (p_1 - c_1)q_1 - (hT-o)^b q - \mu\int_0^{q_1} v^b vqf(D)dD\\ &+ \int_{q_1}^{\alpha_1}(1-\rho k)(p-c_1)r(D-q_1) + v\left(q_1 + {}^b q - D\right)f(D)dD.\end{aligned} \tag{A.3}$$

The first-order derivative of $g(\pi_3(q_1, {}^bq_2, b_q))$ with respect to φ is

$$\frac{\partial g(\pi_3(q_1, {}^bq_2, b_q))}{\partial \varphi} = 1 - \frac{1}{1-\eta} F\left(\frac{(p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k)r)(p - c_1)^b q - \varphi}{\mu v}\right). \tag{A.4}$$

Therefore, it can be obtained that under η, the optimal value at risk φ^* is

$$\varphi^* = (p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k)r(p - c_1))^b q - \mu v F^{-1}(\eta). \tag{A.5}$$

The objective function can be rewritten as follows:

$$H(\pi_3(q_1, {}^bq_2, b_q)) = (p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k)r(p - c_1))^b q + \frac{\mu v}{\eta} \int_0^{F^{-1}(\eta-1)} F(D)dD. \tag{A.6}$$

When φ^* is known, the first-order derivative of $H(\pi_3(q_1, {}^bq_2, b_q))$ with respect to q_1 is

$$\frac{\partial H(\pi_3(q_1, {}^bq_2, {}^bq))}{\partial^b q} = -\mu(hT - o + (1-\rho k)r(p - c_1)) \leq 0, \tag{A.7}$$

from (A.4), we conclude that the formula cannot output an optimal solution. So the risk-averse supplier 1 has no optimal reserves in this case.

Case A.3. By the same token $\varphi \geq (p_1 - c_1)q_1 - (hT - o)^b q + \mu v^b q$, $\varphi < (p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k)r)(p - c_1)^b q_2$, it also cannot output an optimal solution.

Case A.4. $\varphi \geq (p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k)r)(p - c_1)^b q$, the solution principle of conditional CVaR can be obtained for arbitrary fixed. According (19), we can obtain

$$\varphi^* = (p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k)r)(p - c_1)^b q. \tag{A.8}$$

The objective function can be rewritten as follows:

$$\begin{aligned} H(\pi_3(q_1, {}^bq_2, b_q)) = {} & (p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k)r(p - c_1))^b q \\ & + \frac{\mu v}{\eta} \int_0^{q_1 + b_q} F(D)dD + \frac{\mu(1-\rho k)(p - c_1)r}{\eta} \int_{q_1}^{q_1 + b_q} F(D)dD. \end{aligned} \tag{A.9}$$

The first-order derivative of $H(\pi_3(q_1, {}^bq_2, b_q))$ with respect to b_q is

$$\frac{\partial H(\pi_3(q_1, {}^bq_2, b_q))}{\partial^b q} = -\mu(hT - o + (1-\rho k)r(p - c_1)) - \left(\frac{\mu v}{\eta} - \frac{\mu(1-\rho k)(p - c_1)r}{\eta}\right) F(q_1 + b_q) = 0. \tag{A.10}$$

The supplier 1's optimal reserve in this case is

$${}^b q^* = F^{-1}\left(\frac{\eta(hT - o + ((1-\rho k)(p - c_1)))}{v - (1-\rho k)(p - c_1)r}\right) - q_1. \tag{A.11}$$

Case A.5. $\varphi \geq (p_1 - c_1)q_1 - \mu(hT - o + (1-\rho k))r(p - c_1)^b q_2$, the solution principle of conditional CVaR can be obtained for arbitrary fixed. For the same reason, we can obtain the supplier 2's optimal reserve in this case is

$${}^b q_2^* = F^{-1}\left(\frac{\eta(hT - o + (1-r)\rho k(p_2 - c_2))}{v - (1-r)(p - c_1)\rho k}\right) - q_1. \tag{A.12}$$

Proof of Proposition A.4. By (24), the value range of is discussed as follows □

Case A.6. $\varphi \geq p_1 q_1 + hTq_1 + oq^* + \mu v q_1$, in this case, given (24), we can obtain $g(C(q_1, q_2, q^*)) = \varphi$. The first-order derivatives of $g(C(q_1, q_2, q^*))$ with φ, respect to, we have the risk-averse government's expected cost decrease with the value at risk.

Case A.7. $\varphi < p_1q_1 + hTq_1 + oq^* - \mu v q_1$, $\varphi \geq p_1q_1 + hTq_1 + oq^*$, we have $\beta_1 = -\varphi + p_1q_1 + hTq_1 + oq^* - \mu v q_1/\mu v < q_1$. If and only if the government's order quantity is $(0, \beta_1)$, we get

$$gCq_1, q_2, q^* = \varphi + \frac{1}{1-\eta} 1 - \mu v q_1 + \int_0^{\beta_1} \varphi - p_1q_1 - hTq_1 - oq^* + \mu v D - q_1 f(D) dD. \quad \text{(A.13)}$$

The first-order derivative of $g(C(q_1, q_2, q^*))$ with respect to φ is

$$\frac{\partial g(C(q_1, q_2, q^*))}{\partial \varphi} = 1 - \frac{1}{1-\eta} F\left(\frac{-\varphi + p_1q_1 + hTq_1 + oq^* - \mu v q_1}{\mu v}\right). \quad \text{(A.14)}$$

Therefore, it can be obtained that under η, the optimal value at risk φ^* is

$$\varphi^* = p_1q_1 + hTq_1 + oq^* - \mu v q_1 - \mu v F^{-1}(\eta - 1). \quad \text{(A.15)}$$

The objective function can be rewritten as follows:

$$H(C(q_1, q_2, q^*)) = p_1q_1 + hTq_1 + oq^* + \mu v q_1 - \mu v F^{-1}(\eta - 1) + \frac{v}{1-\eta}\left((1-\mu)q_1 + \int_0^{F^{-1}(\eta-1)} F(D)\right) dD. \quad \text{(A.16)}$$

When φ^* is known, the first-order derivative of $H(C(q_1, q_2, q^*))$ with respect to q_1 is

$$\frac{\partial H(C(q_1, q_2, q^*))}{\partial q_1} = p_1 + hT + \mu v + \frac{v}{1-\eta} > 0, \quad \text{(A.17)}$$

from (A.14), we conclude that the formula cannot output an optimal solution. So the risk-averse government has no optimal reserves in this case.

Case A.8. $\varphi < p_1q_1 + hTq_1 + oq^* - \mu v q_1$, $\varphi \geq p_1q_1 + hTq_1 + oq^* + \mu((1-r)\rho k p_2 q_2 + r(1-\rho k)pq^*)$, we obtain $\beta_2 = \varphi - p_1q_1 - hTq_1 - oq^* + \mu((1-r)\rho k p_2 q_1 + (1-\rho k)prq_1)/\mu((1-r)\rho k p_2 + (1-\rho k)rp)$. If and only if $\beta_2 \in (q_1, q_1 + q^*)$, the government has an expected cost greater than the value at risk.

$$\begin{aligned} g(C(q_1, q_2, q^*)) = \varphi + \frac{1}{1-\eta}\Big(&(1-\mu)vq_1 \\ &+ \int_0^{q_1} (\varphi - p_1q_1 - hTq_1 - oq^* + \mu v(D - q_1)) f(D) dD \\ &+ \int_{q_1}^{\beta_2} (\varphi - p_1q_1 - hTq_1 - oq^* - \mu\rho k p_2(1-r) + (1-\rho k)rp)(D - q_1) f(D) dD\Big). \end{aligned} \quad \text{(A.18)}$$

The first-order derivative of $g(C(q_1, q_2, q^*))$ with respect to φ is

$$\frac{\partial g(C(q_1, q_2, q^*))}{\partial \varphi} = 1 + \frac{1}{1-\eta} F\left(\frac{\varphi - p_1q_1 - hTq_1 - oq^* + \mu(\rho k p_2(1-r) + (1-\rho k)pr)q_1}{\mu((1-r)\rho k p_2 + (1-\rho k)rp)}\right), \quad \text{(A.19)}$$

by the first-order optimality condition, we obtain the optimal value at risk as follows:

$$\varphi^* = p_1q_1 + hTq_1 + oq^* - \mu((1-r)\rho k p_2 + (1-\rho k)pr)q_1 + \mu F^{-1}(\eta - 1)\mu((1-r)\rho k p_2 q_2 + ((1-\rho k))rpq^*). \quad \text{(A.20)}$$

The objective function can be rewritten as follows:

$$\begin{aligned}H(C(q_1,q_2,q^*)) &= p_1q_1 + hTq_1 + oq^* - \mu((1-r)\rho kp_2 + (1-\rho k)pr)q_1\\&\quad + \mu F^{-1}(\eta-1)((1-r)\rho kp_2q_2 + (1-\rho k)prq^*) + \frac{1}{1-\eta}(1-\mu)vq_1\\&\quad + \frac{\mu v}{1-\eta}\int_0^{q_1}F(D)dD - \frac{\mu((1-r)\rho kp_2q_2 + (1-\rho k)rpq^*)}{1-\eta}\int_{q_1}^{F^{-1}(\eta-1)}F(D)dD.\end{aligned}\tag{A.21}$$

The first-order derivative of $H(C(q_1,q_2,q^*))$ with respect to q_1 is

$$\frac{\partial H(C(q_1,q_2,q^*))}{\partial q_1} = p_1 + hT + \frac{(1-\mu)v}{1-\eta} + \frac{\mu(v+\rho kp_2 + (1-\rho k)p)}{1-\eta}F(q_1) > 0,\tag{A.22}$$

by (A.19), we conclude that the formula cannot output an optimal solution. So the risk-averse government has no optimal reserves in this case.

Case A.9. $\varphi < p_1q_1 + hTq_1 + oq^* + \mu((1-r)\rho kp_2q_2 + (1-\rho k)pq^*)$, $\varphi \geq p_1q_1 + hTq_1 + oq^* + \mu((1-r)\rho kp_2 + r(1-\rho k)w)(q_1 + q^* + S)$, we obtain $\beta_3 = \varphi - p_1q_1 - hTq_1 - oq^* - \mu((1-r)\rho kp_2)/\mu((1-r)\rho kw + r(1-\rho k)w) + r((1-\rho k)p)q^*/\mu((1-r)\rho kw + r(1-\rho k)w)$. If and only if $\beta_3 \in (q_1 + q^*, q_1 + q^* + S)$, the government has an expected cost greater than the value at risk.

$$\begin{aligned}g(C(q_1,q_2,q^*)) &= \varphi + \frac{1}{1-\eta} - (1-\mu)vq_1 + \int_0^{q_1}(\varphi - p_1q_1 - hTq_1 - oq^* + \mu v(D-q_1))f(D)dD\\&\quad + \int_{q_1}^{q_1+q^*}\varphi - p_1q_1 - hTq_1 - oq^* - \mu((1-r)\rho kp_2 + (1-\rho k)pr)(D-q_1)f(D)dD\\&\quad + \int_{q_1+q^*}^{\beta_3}(\varphi - p_1q_1 - hTq_1 - oq^* - \mu(((1-r)\rho kp_2q_2 + r(1-\rho k)prq^*)f(D)dD)).\end{aligned}\tag{A.23}$$

The first-order derivative of $g(C(q_1,q_2,q^*))$ with respect to φ is

$$\frac{\partial g(C(q_1,q_2,q^*))}{\partial\varphi} = 1 + \frac{1}{1-\eta}F\left(\frac{\varphi - p_1q_1 - hTq_1 - oq^*}{\mu((1-r)\rho kw + r(1-\rho k)w)} + \frac{\mu((1-r)\rho kp_2q_2 + r(1-\rho k)rpq^*)}{\mu((1-r)\rho kw + r(1-\rho k)w)}\right).\tag{A.24}$$

By the first-order optimality condition, we obtain the optimal value at risk as follows:

$$\varphi^* = p_1q_1 + hTq_1 + oq^* - \mu((1-r)\rho kp_2q_2 + r(1-\rho k)pq^*) - F^{-1}(\eta-1)\mu((1-r)\rho k + r(1-\rho k))w.\tag{A.25}$$

The objective function can be rewritten as follows:

$$\begin{aligned}H(C(q_1,q_2,q^*)) &= p_1q_1 + hTq_1 + oq^* + \mu((1-r)\rho kp_2q_2 + r(1-\rho k)pq^*) - \mu F^{-1}(\eta-1)((1-r)\rho kw \\ &\quad + (1-\rho k)w) + \frac{1}{1-\eta}((1-\mu)vq_1) \\ &\quad + \frac{\mu v}{1-\eta}\int_0^{q_1} F(D)dD - \frac{\mu(((1-r)\rho kw + r(1-\rho k))w)}{1-\eta}\int_{q_1}^{F^{-1}(\eta-1)} F(D)dD.\end{aligned} \tag{A.26}$$

The first-order derivative of $H(C(q_1,q^*,q_2))$ with respect to q_1 is

$$\begin{aligned}\frac{\partial H(C(q_1,q_2,q^*))}{\partial q_1} &= p_1 + hT + \frac{(1-\mu)v}{1-\eta} \\ &\quad + \frac{\mu(v-(1-r)\rho kw + r(1-\rho k)w)}{1-\eta}F(q_1) > 0,\end{aligned} \tag{A.27}$$

by (A.24), we conclude that the formula cannot output an optimal solution. So the risk-averse government has no optimal reserves in this case.

Case A.10. $\varphi < p_1q_1 + hTq_1 + oq^* + \mu((1-r)\rho kw + r(1-\rho k)w)(q_1 + q^* + S)$, the solution principle of conditional CVaR can be obtained for arbitrary fixed q_1.

$$\begin{aligned}g(C(q_1,q_2,q^*)) &= \varphi + \frac{1}{1-\eta}p_1q_1 + hTq_1 + oq^* - (1-\mu)vq_1 + \mu\int_0^{q_1}(\varphi - v(D-q_1))f(D)dD \\ &\quad + \int_{q_1}^{q_1+q^*}(\varphi - ((1-r)\rho kp_2 + r(1-\rho k)p)(D-q_1))f(D)dD \\ &\quad + \int_{q_1+q^*}^{U}([\varphi - (1-r)\rho kp_2q_2 - r(1-\rho k)p]q^*)f(D)dD \\ &\quad + \int_{q_1+q^*+S}^{U}([\varphi - ((1-r)\rho kw + r(1-\rho k)w)(D-q_1-q^*-S)]f(D)dD),\end{aligned} \tag{A.28}$$

which means that

$$\begin{aligned}\varphi^* &= p_1q_1 + hTq_1 + oq^* + \mu((1-r)\rho kw \\ &\quad + r(1-\rho k)w)(q_1 + q^* + S).\end{aligned} \tag{A.29}$$

The objective function can be rewritten as follows:

$$\begin{aligned}H(C(q_1,q_2,q^*)) &= p_1q_1 + hTq_1 + oq^* + \mu((1-r)\rho kw + r(1-\rho k)w)(q_1 + q^* + S) - \frac{1}{1-\eta}(1-\mu)vq_1 \\ &\quad + \frac{\mu(1-r)\rho kp_2}{1-\eta}\int_0^{q_1+q^*+S} F(D)dD - \frac{\mu(1-\rho k)p}{1-\eta}\int_{q_1}^{q_1+q^*+S} F(D)dD.\end{aligned} \tag{A.30}$$

The first-order derivative of $H(C(q_1,q^*,q_2))$ with respect to q_1 and q^* are

$$\begin{aligned}\frac{\partial H(C(q_1,q_2,q^*))}{\partial q_1} &= p_1 + hT - \frac{(1-\mu)v}{1-\eta} \\ &\quad + \frac{\mu r(1-\rho k)p}{1-\eta}F(q_1) = 0.\end{aligned} \tag{A.31}$$

The government's optimal reserve in this case is

$$q_1^* = F^{-1}\left(\frac{(1-\mu)v - (1-\eta)(p_1 + hT)}{\mu r(1-\rho k)p}\right). \tag{A.32}$$

Proof of Proposition A.5. For the rest of the following discussing, we define $I = (1-\mu)v - (1-\eta)(p_1 + hT)/\mu r(1-\rho k)p$, and we need to use the first-order derivative of I with respect to T, η, μ that we can get

$$\frac{\partial I}{\partial T} = \frac{-(1-\eta)h}{\mu(1-\rho k)p} < 0,$$
$$\frac{\partial I}{\partial \eta} = \frac{p_1 + hT}{\mu(1-\rho k)p} > 0, \tag{A33}$$
$$\frac{\partial I}{\partial \mu} = \frac{r\left((1-\rho k)p(1-\eta)\left(p_1 + hT\right) - v\right)}{\mu^2 (1-\rho k)^2 p^2} > 0.$$

Owing to $F^{-1}(D)$ is an increasing function, the proof is completed. □

Proof of Proposition A.6. For the sake of calculation, we assume that demand follows a uniform distribution, from (6) and (13), namely, ${}^{b}q^{*} = q_1^{*}$. We can obtain

$$o^{*} = hT - v - \mu(1-\rho k)r + 2\left(\frac{\left(p_1 + hT - v - \mu v\right)\left(\mu r(1-\rho k)\left(1 - p_1 - c_1\right)\right)}{\mu\left((1-\rho k)pr + \rho k p_2 (1-r) - v\right)}\right), \tag{A.34}$$

from (13) and (16), namely, $q_1^{*} \geq q_0^{*}$. We can obtain

$$p^{*} \leq \frac{U\left(\rho k p_2 (1-r)(\mu S - 1)\right)}{U\left(\mu r(1-\rho k)(1+\mu S)\right)}. \tag{A.35}$$

□

Data Availability

The [DATA TYPE] data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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