Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
March-April 2022 Page No. 240-262
Article History: Received: 08 February 2022, Revised: 10 March 2022, Accepted: 02 April 2022, Publication: 30 April 2022

Joint Reserve Decision-making of Emergency Supplies in Response to Emergencies

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Abstract:

This paper analyzes and studies the demand for emergency supplies, the process of reserve and the way and influencing factors of supplies reserve, etc. The joint reserve method formed by combining production capacity reserve and physical reserve is taken as the way of emergency supplies reserve. This supplies reserve method combines the advantages of physical reserve and production capacity reserve. Through quantitative analysis, the physical reserve of emergency supplies, the production capacity reserve, and the subsidies provided to enterprises are calculated. Finally, the case study illustrates that this method is effective in saving resources and reducing the cost of emergency supplies and increasing the profit of enterprises, while ensuring a certain amount of emergency supplies.

Keywords*: Emergency, Emergency supplies, Supplies reserves, Reserve.*

I. INTRODUCTION

1.1 Research background

In recent years, many natural disasters or emergencies have occurred in China, which are of great social harm and wide coverage. They are difficult to predict accurately, affecting a large number of people. For these natural disasters or emergencies, it is difficult for anyone or any organization to make targeted plans before they happen. Moreover, it is impossible to determine and calculate the varieties and quantities of necessary supplies. After the occurrence of an emergency, it may also appear that the state has difficulty in meeting the type and quantity of the corresponding emergency supplies within a short period of time. Emergency supplies are a necessary resource to solve the emergency situation. If they cannot be effectively supplied to the urgent areas, it may make the harm or impact of the accident become uncontrollable in a short period of time, causing the expansion of the scope of the accident harm, or even causing new accidents. This will seriously threaten the safety of people's lives and property and affect social stability, or even worse, will cause social panic. For example, the inadequate provision of medical supplies in the early stages of the COVID-19 epidemic caused the difficulty of controlling the epidemic in its early stage. Besides, the price of many supplies in the market rose wildly, resulting in a rush to buy household supplies.

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To ensure the most efficient rescue rate, the most timely treatment of the sick and injured and the shortest time to control the various influences of the accident and eliminate the threats that may arise from the accident, the goal of the emergency supplies reserve is to meet the material needs of emergency treatment. Thus, the timely and effective provision of emergency supplies has become the key, which also shows the importance of the emergency supplies reserve[1]. So far, although China has published literature and acts on relief supplies reserve, established the disaster relief supplies reserve system, and set up numerous agent storage institutions for relief reserves throughout the country, it still seems insufficient in past practice. Whether it is the provision of basic living supplies in the Wenchuan Earthquake in 2008 or the provision of medical supplies required for the COVID-19 epidemic in 2020, China's emergency supplies reserve is still in the state of "breaking the pale". Therefore, the way of emergency supplies reserve and management system in China still need to be optimized and improved.

1.2 Research significance

Starting from the demand for emergency supplies required by emergencies, this paper explores the optimal decision-making of national physical reserves and social production reserve capacity under uncertain emergencies, considering the constraints of sources and costs of social supplies. The significance of this research mainly includes the following points:

(1) Rapid replenishment of insufficient supply of physical reserves; due to the randomness of the time, type and scale of emergencies, the type and quantity of physical reserves are also uncertain. In the past experience, it can be seen that the demand and consumption rate of emergency supplies in emergencies are large, and the supplies that can play a role in physical reserve are very limited, while the production capacity reserve of enterprises can provide necessary supplies quickly and on a large scale, reducing the quantity and cost of emergency production and emergency procurement, and making up for the shortage of physical reserve mode.

(2) Reduction of the cost of storage and management; at present, most of the emergency supplies needed to deal with various emergencies in China are stored in physical reserve, which causes large quantity and large scale of the physical reserve and leads to huge management and maintenance costs. However, using the enterprise's production capacity reserve can directly deliver the produced products to the demand places, which reduces the links of "warehousing" and "secondary transportation" compared with the physical reserve, and sharply reduces the storage, transshipment and other expenses.

(3) Improvement of the state’s ability to respond to emergencies; from the perspective of game theory, this paper analyzes and finds the balance point between the cost and benefit of the participation of the state and enterprises in the joint reserve. By giving corresponding financial countermeasures and suggestions, more enterprises will be willing to join the state's emergency supplies reserve, thus improving the state's ability to cope with emergencies[2].

(4) Improvement of the flexibility of enterprise production. Enterprises' participation in the process of

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emergency supplies reserve can be said to be a process of adapting to the rapid changes of market conditions in a short period of time, because the demand for emergency supplies is a special social demand, which not only tests the ability of enterprises to produce rapidly with high quality, but also tests their ability to give consideration to both "demand" and "forecast". Therefore, in this process, the ability of enterprises to supply and respond quickly to the market and the flexibility of production transformation are improved.

II. BASIC INTRODUCTION OF EMERGENCY SUPPLIES RESERVE

2.1 Overview of emergency supplies

Emergency supplies reserves are used by the state to ensure national security and respond to war, natural disasters and other possible unexpected events or to effectively regulate the macroeconomic operation of the national economy.

2.1.1 Demand for emergency supplies

(1) The requirement for the varieties of emergency supplies. There are many kinds of emergencies in China, which are mainly divided into four categories, namely, accidents and disasters, natural disasters, public health and social security[3]. Although many emergency supplies are necessary and universal when all kinds of emergencies occur, each kind of emergency has its own unique characteristics, and there is a certain pertinence when dealing with them. Therefore, when dealing with different emergencies, there will always be some supplies with strong pertinence. The diversity of emergency supplies is a major influencing factor of supplies reserve and management, and meeting the diversity of emergency supplies is one of the influences on the timeliness and effectiveness of emergency response.

(2) The requirement for the quantity of emergency supplies. To deal with emergencies in a timely and effective manner, and to prevent accidents from being uncontrollable or expanding again, it is essential to meet the requirement for the quantity of emergency supplies. Usually, the larger the population density of the accident site, the wider the coverage and the higher the risk level, the greater the quantity of emergency supplies needed[4].

(3) The requirement for the quality of emergency supplies. The requirement for the quality of emergency supplies is mainly reflected in their pertinence, practicability, safety and other aspects. The supplies prepared when an accident occurs should be fully utilized, and each item should be effective when dealing with the accident.

(4) The requirement for the structure of emergency supplies. The proportion between operators and supplies and the proportion between beneficiaries and supplies are mainly taken into account.

2.1.2 Process of emergency supplies reserve

The period of emergency is the time interval from the end of one emergency event to the end of the

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next. The process of emergency supplies reserve is a series of activities to fully meet the demand for emergency supplies in a cycle of various emergencies. This process is shown in Fig 1, which mainly includes demand forecasting stage, supplies reserve stage and evaluation stage. The main activity of the demand forecasting stage is to forecast the varieties, quantity, quality and structure of emergency supplies needed for the next or ongoing emergencies based on the actual experience of dealing with emergencies in the past. In the stage of supplies reserve process, the results of demand forecasting stage are mainly used as reserve targets, and supplies are reserved by various means and methods. The main work content of the evaluation stage is to estimate and calculate the actual demand for emergency supplies when emergencies occur. If the existing reserved supplies are insufficient to meet the actual demand, the work in the supplies reserve stage needs to be carried out again.

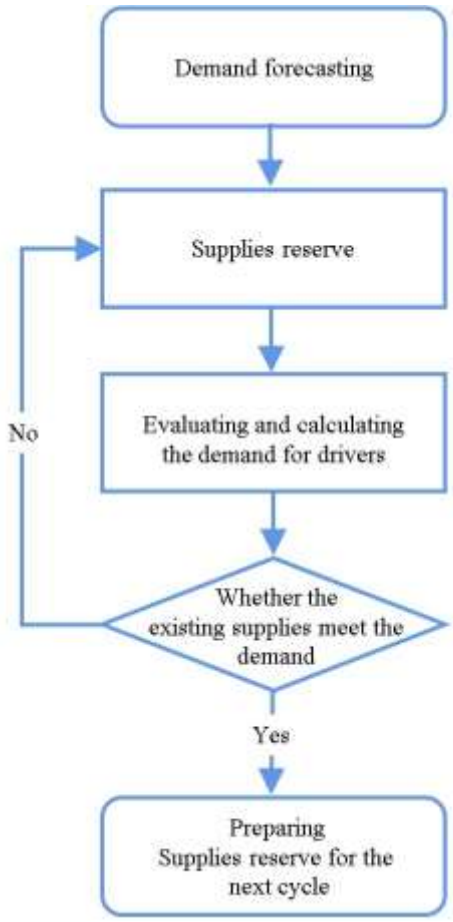

Fig 1: Process of emergency supplies reserve

2.2 Supplies reserve mode

Because of the different uses, control links and other factors, the reserve methods of supplies are also different.

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2.2.1 Physical reserve

(1) Overview of physical reserve

Physical reserve is to store the necessary supplies in advance to cope with emergencies. When an emergency occurs, the reserved supplies are directly transported to the emergency site. It is a traditional and main supplies reserve mode in China. In this mode, the central and local governments build or rent warehouses, purchase supplies and store them, and manage the warehouses and stored supplies. In this mode, the state can respond quickly to emergencies, provide supplies within a certain period of time, and guarantee the timeliness of material supply to the maximum extent[5]. However, under this mode, a series of work such as warehouse management, procurement, maintenance and renewal of construction supplies have to be implemented by the state, so huge manpower and material resources are needed, which exerts great pressure on the state in terms of financial resources and management. Therefore, this mode is only suitable for storing necessary living supplies and supplies with strong timeliness and difficulty in obtaining.

(2) Problems and deficiencies of physical reserve

Although in recent years, China has been continuously strengthening and attaching importance to the security system of emergency supplies and expanding the reserve points and reserves of emergency supplies, there is still a shortage of emergency supplies when emergencies occur. Although China is a big manufacturing country, due to the complexity, correlation and interaction of human society, even with the warning of SARS, many anti-epidemic medical supplies could not be supplied immediately when the COVID-19 epidemic occurred. There was even serious shortage in a short period of time, which was really unexpected. One of the reasons for this situation is the shortage of anti-epidemic supplies in China. The shortage of material supply can be said to be the shortage of "resource allocation", which includes the shortage of national reserves and the shortage of finished products provided by social enterprises. The practice of relying only on the state to carry out physical stockpiling of emergency materials to meet the material needs of emergencies, although theoretically feasible, has many limitations and is only applicable to emergencies with small scale, less difficulty to control and fewer victims.

At present, there are still many shortcomings in China's emergency supplies reserve, mainly including:

1) Small reserve. Due to the uncertainty and unpredictability of emergencies and other factors, it is difficult to ensure that the emergency supplies reserve can reach 100% of the emergency support rate.

2) Less varieties. Most of the reserves store the supplies needed for all kinds of emergencies, such as daily necessities, medicines, tools and equipment, while there are fewer supplies necessary for certain emergencies, such as life detectors for earthquake relief and medical protective clothing for public health events.

3) Poor support ability. There is a lack of scientific guidance when evaluating the support capability of emergency supplies, which makes the emergency supplies reserve unreasonable in structure and mode[6].

4) Scattered reserve points and the lack of the management system of overall planning. The main body of China's emergency supplies reserve is the people's governments above the municipal level as well as the people's governments at the county level in areas where emergencies are prone to occur frequently[7]. Different regions mainly set up reserve points and corresponding supplies and quantities according to their

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forecasted demand. Most regions lack sufficient contact and communication in the establishment of emergency supplies reserve system and in the planning and storage of physical reserves, and the supplies are managed separately, thus resulting in problems such as low coordination, redundant construction and reduction of the effectiveness and rationality of capital investment[8].

5) Backward reserve facilities and methods. As the funds for the construction of reserve warehouses should be raised by local governments, there are capital and technological restrictions, causing low warehouse construction level and professional information digitization level[9].

6) High maintenance, storage and management costs of supplies. Some supplies' have their own characteristics. For example the disinfectant needs to be kept in a specific environment, and its effectiveness needs to be checked irregularly. For unused supplies that have exceeded the shelf life, they need to be treated and replaced.

2.2.2 Production capacity reserve

(1) Overview of production capacity reserve

Productive capacity refers to the ability of enterprises to provide certain products for society in a certain period of time[10]. Production capacity reserve is the state's forecast of the demand for emergency supplies. By signing some agreements with enterprises with surplus production capacity in the society, these enterprises are required to quickly formulate new production plans, adjust production lines, and provide enough products that meet the use quality requirements in a short period of time when the demand for certain kinds of supplies suddenly increases sharply due to emergencies and the consumption of supplies in physical reserves is insufficient to supply the demand for emergency supplies. Therefore, production capacity reserve can save inventory cost and reduce the risk of insufficient physical reserves[11].

(2) Applicable scope of production capacity reserve

Production capacity reserve is different from physical reserve. It is not necessary to reserve a large amount of spare supplies in real time. The enterprises only need to reserve surplus production capacity to provide necessary products when necessary. Such products are often products with special purpose, large demand, difficult maintenance or short effective time. They are emergency supplies with short production cycle, fast transformation speed and easily available product raw materials.

2.2.3 Joint reserve

(1) Overview of joint reserve

Under the mode of joint reserve, the state only needs to store less emergency supplies. Then, through providing certain subsidies and preferential policies to enterprises, the state can reach certain agreements by cooperation, thus turning emergency supplies into surplus production capacity of enterprises and handing it over to enterprises for reserve[12]. This reserve mode is beneficial to both the state and the enterprises, and their reserve modes can work together when emergencies occur[13]. The goal of joint reserve is to minimize the reserve and maximize the enterprise profit. For the state, it can reduce the management and maintenance fees necessary for the physical reserve and the losses caused by the expiration of the validity period of the physical reserve. For enterprises, they get the subsidies which can reduce the degree of risk avoidance of cooperation, and are exercised in the flexibility of production. Moreover, their ability of market supply and quick response is also improved[14].In this mode, the state

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retains certain physical reserves and has a certain emergency support capability. At the same time, the mode reduces the risk of material shortage and storage costs, effectively reduces emergency production and procurement, thus making the supply of emergency supplies more flexible[15].

From the above analysis, it can be seen that the reserve of physical emergency supplies is necessary and effective for solving emergencies, but it is not timely and efficient. Due to various uncertainties and unpredictability of emergencies, it is difficult to accurately predict the varieties and quantities of emergency supplies. Nowadays, it is backward and inefficient to rely solely on the traditional supplies reserve strategy to deal with emergencies. Therefore, to effectively deal with various emergencies, it is necessary to adopt new supplies reserve methods to deal with uncertain demands[16]. With the development of science and technology, the efficiency and mode of enterprise production products are constantly improving and changing. As a new supplies reserve mode, enterprise production capacity reserve can now be realized. It can provide necessary supplies in a short time by expanding the production of specific emergency supplies through rapid production transformation, which changes the traditional physical reserve mode and makes the research on joint reserve of emergency supplies practical.

(2) Influencing factors of joint reserve

The main decision-maker of supplies reserve under the mode of joint reserve is the state, and the supplies reserve for decision-making should be determined according to the demand, total cost, basic guarantee rate and other factors. The actual storage capacity, timeliness, purchase price and other factors should also be considered. In the decision-making process of joint reserve, we should not only consider the total amount of supplies needed, but also determine the proportion of physical reserve and production capacity reserve [17], and strive for the lowest cost under the premise of ensuring the basic guarantee level.

The important influencing factors of joint reserve decision-making are: demand, timeliness, reserve period, reserve cost, basic guarantee rate and warehouse limitation. The relationship between influencing factors and between their sub-influencing factors is shown in Fig 2.

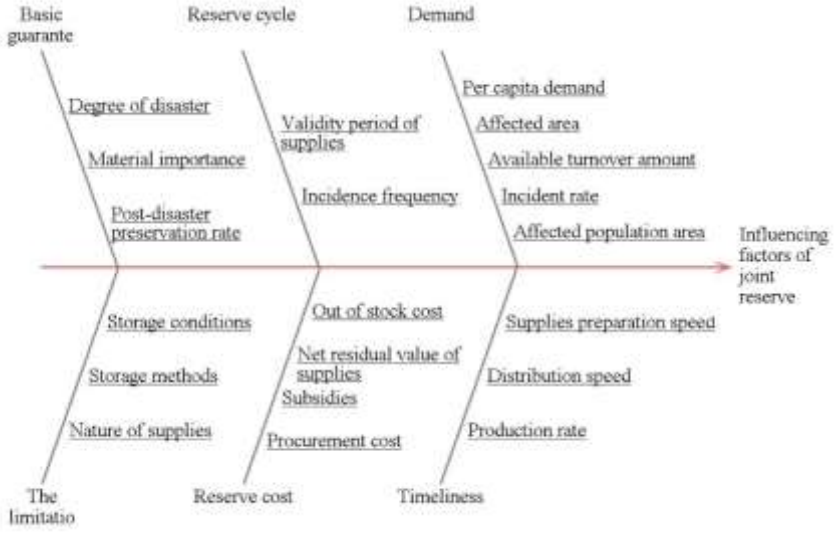

Fig 2: Influencing factors of joint reserve

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Ⅲ. ESTABLISHMENT OF JOINT RESERVE MODEL

For the joint reserve mode, the emergency supplies reserve in response to emergencies is modeled as the research object.

3.1 Model parameters

(1) When an emergency occurs, the demand for emergency supplies is X, and its maximum value is M. X is a random variable. Its distribution function is $F(X)$, and its density function is $f(X)$.

(2) Physical reserve$Q_g$and production capacity reserveQ_s ($Q_g \geq 0, Q_s \geq 0$).

(3) The state provides subsidies $T(T \geq 0)$ for the production capacity reserve of social enterprises per unit quantity.

(4) The management fee $H(H \geq 0)$ for the state to store the unit quantity of physical supplies.

(5) The net salvage value $\omega(\omega \geq 0)$ of unused unit quantity of reserved supplies when the supplies are larger than items needed after the emergency occurs.

(6) The normal market price $P_1(P_1 \geq 0)$ of the unit items purchased by the state from enterprises during supplies reserve.

(7) The price $P_2(P_2 \geq 0)$ of unit items produced by the production capacity reserve of social enterprises acquired by the state.

(8) The price $P_3(P_3 \geq 0)$ of unit items that the state urgently purchases by other means after the emergency occurs.

(9) The production cost $C(C>0)$per unit item of the enterprise.

(10) The cost $N(N>0)$of production capacity reserve or product transformation preparation per unit quantity of the enterprise.

Assumptions of parameters: P_1, P_2 and P_3 are unique and unchangeable. That is, the normal market price of purchased emergency supplies, the price of supplies produced by production capacity reserve and the price of urgently purchased goods are invariable at any time and from any supplier; $P_3 > P_2 \geq P_1 > \omega$. That is, the price of urgently purchased supplies is higher than that of normal market price and the price of enterprise transformation; P_2 is determined by the social demand. When the production capacity reserve is used, the required supplies are often in short supply, which leads to the market price increase. Therefore, the price of supplies may be higher than the normal market price at this time; the net salvage value of unused reserved supplies is lower than the normal market price, the price of enterprise transformation and the emergency purchase price.

3.2 Establishment of emergency supplies reserve model

There are many modes of emergency supplies reserve. But no matter in which mode, the decision-making should give priority to the total amount of emergency material demand, which is the premise to ensure the effect of responding to emergency. At the same time, it is necessary to make

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effective use of funds and control the cost of emergency supplies reserve [15]. Under each reserve mode, the basic guarantee level of emergency supplies should not be lower than that under the condition that the state only reserves in kind. That is, the total amount of emergency supplies should not be less than that under the condition that the state only reserves in kind. On this basis, the optimal physical reserves and production capacity reserves in decision-making and the amount of subsidies provided by the state for social enterprises should be determined with the aim of minimizing the cost of supplies reserves and increasing the enterprise profit.

3.2.1 Establishment of physical reserve decision-making model

(1) Supplies acquisition under physical reserve mode

The acquisition of emergency supplies mainly considers the two stages before and after the emergency. Before the accident, the forecasted supplies needed are purchased from the enterprise. After the accident, if the existing supplies are insufficient to meet the actual demand, emergency procurement is carried out.

(2) Reserve cost and enterprise profit

When making decisions only on physical reserves, it is only necessary to determine the physical reserves of the state. In the mode of physical reserve only, the physical reserve is $\mathrm{Q_{g1}}$.

Under the physical reserve mode, the expectation of the expenses incurred by the state in supplies reserve is as follows:

$$E_{c1} = P_1 Q_{g1} + H Q_{g1} - \int_0^{Q_{g1}} \omega\left(Q_{g1} - X\right) f(\mathrm{X}) dX + \int_{Q_{g1}}^{M} P_3 \left(X - Q_{g1}\right) f\left(X\right) dX \qquad (1)$$

The first part on the right side of equation (1) refers to the expenses for purchasing physical supplies before the emergency; the second part is the management fee for storing the purchased physical supplies; the third part is the expected residual value of unused supplies when the physical reserve Q_{g1} exceeds the actual demand X after the emergency; the fourth part is the expected cost of physical supplies purchased urgently from outside when the actual demand X exceeds the physical supplies reserve Q_{g1} after the emergency.

After conducting the derivation analysis of equation (1), and letting $\frac{\partial E_{C1}}{\partial Q_{g1}} = 0$, the physical reserves when the national cost is the least can be obtained:

$$Q'_{g1} = F^{-1}\left(\frac{P_3 - P_1 - H}{P_3 - \omega}\right), (P_3 > P_1 + H) \qquad (2)$$

Therefore, in the physical reserve mode, the physical reserve is:

$$Q_{g1} = \begin{cases} Q'_{g1}, & P_3 > P_1 + H \\ 0, & \text{Other} \end{cases} \qquad (3)$$

Letting the state's physical reserves be Q_{g2}, and the profit of the enterprise at this time is:

$$E_{W1} = Q_{g2}(P_1 - C) \qquad (4)$$

The expected profit of the overall benefit composed by the state and enterprises is:

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$$E_{Z1} = E_{W1} - E'_{c1}$$

$$= -CQ_{g2} - HQ_{g2} + \omega \int_0^{Q_{g2}} F(X)\,dX - P_3[M - Q_{g2} - \int_{Q_{g2}}^{M} F(X)\,dX] \quad (5)$$

After conducting the derivation analysis of equation (5), and letting$\frac{\partial E_{Z1}}{\partial Q_{g2}}$ =0, the supplies reserves of the state with the largest expected profit of overall benefit can be obtained as follows:

$$Q'_{g2} = F^{-1}(\frac{C+H-P_3}{\omega-P_3}) \ , (P_3>C+H) \quad (6)$$

Therefore, when the expected profit of the overall benefit is maximum, the physical reserves are:

$$Q_{g2} = \begin{cases} Q'_{g2}, & P_3 > C + H \\ 0, & \text{Other} \end{cases} \quad (7)$$

LettingQ'_{g2} be the quantity of emergency supplies required by the state to reach the basic guarantee level when making physical reserves, under the decision-making of various reserve modes, the quantity of emergency supplies cannot be lower than the quantity required by the basic guarantee level.

3.2.2 Establishment of joint reserve decision-making model

The main decision maker under the joint reserve mode is the state, but the enterprise has also become one of the executors. For the state, it is necessary to coordinate and sign agreements with enterprises in advance, and formulate reasonable subsidy policies [17]. Enterprises should adapt to the changes of national plans in real time, dynamically adjust production plans, and consider the issue of profitability. Compared with physical reserves, the difficulty and workload have been increased for both the state and the enterprises. From the perspective of cooperative game theory, if both parties are willing to participate in joint reserve cooperation, it is necessary to ensure that the reserve cost of the state after cooperation is not greater than that before cooperation and the enterprise is not less than that before cooperation[18].

(1) Supplies acquisition under the joint reserve mode

When using the joint reserve mode, the material acquisition process is shown in Fig 3. Before the incident, the state purchases the forecasted supplies from the enterprise for physical reserve, and at the same time, it signs an agreement with the enterprise to reserve its production capacity. After the incident, if the existing supplies are insufficient to meet the actual demand, the state will make emergency purchase.

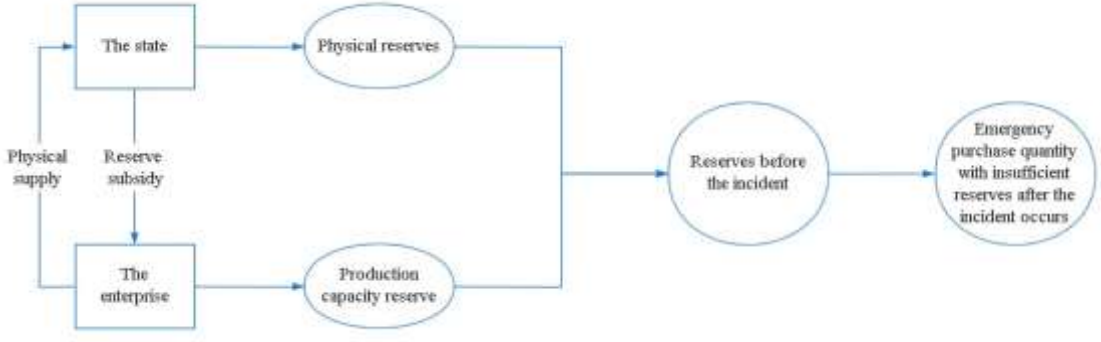

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Fig 3: Supplies acquisition process under joint reserve mode

(2) State cost and enterprise profit

When making decisions under the joint reserve mode, we should consider the state's physical reserves, the required production capacity reserves and the subsidies provided to enterprises. Under the joint reserve mode, the physical reserves of the state are Q_{g3}; the production capacity reserves of enterprises are Q_{s1}; the subsidies provided by the state for enterprises are *T*.

The expected cost of supplies reserve under the joint reserve mode is as follows:

$$E_{C2} = P_1 Q_{g3} + H Q_{g3} + T Q_{s1} - \int_0^{Q_{g3}} \omega\left(Q_{g3} - X\right) f(X) dX + \int_{Q_{g3}}^{Q_{g3}+Q_{s1}} P_2\left(X - Q_{g3}\right) f(X) dX + \int_{Q_{g3}+Q_{s1}}^{M} P_2 Q_{s1} + P_3\left(\mathrm{X} - \left[\mathrm{Q_{g3}} + \mathrm{Q_{s1}}\right]\right) f(X) dX \quad (8)$$

The first part on the right side of equation (8) refers to the cost for purchasing physical supplies before the emergency; the second part is the management fee for storing the purchased physical supplies; the third part is the subsidy for the enterprise production capacity reserve; the fourth part is the expected residual value of unused supplies when the physical reserve Q_{g3} exceeds the actual demand *X* after the emergency; the fifth part is the expected cost of purchasing the supplies produced by enterprise transformation when the physical reserve Q_{g3} is less than the actual demand *X* after the emergency; the sixth part is the expected cost of purchasing supplies produced by enterprise transformation and urgently purchasing supplies from other ways when the actual demand *X* is more than the sum of the physical reserve Q_{g3} and the enterprise production capacity reserve Q_{s1} after the emergency.

The profit of the enterprise is:

$$E_{W2} = (P_1 - C) Q_{g3} + T Q_{s1} - N Q_{s1} + \int_{Q_{g3}}^{Q_{g3}+Q_{s1}} (P_2 - C)(X - Q_{g3}) f(X) dX + \int_{Q_{g3}+Q_{s1}}^{M} (P_2 - C) Q_{s1} f(X) dX \quad (9)$$

The first part on the right side of equation (9) is the profit obtained by the enterprise from selling physical supplies before the emergency; the second part is the subsidy for production capacity reserve obtained by enterprises from the state; the third part is the cost of enterprise product transformation preparation; the fourth part is the expected profit obtained by enterprises selling the supplies produced by transformation according to the agreement when the national physical reserve $Q_{g3}$is less than the actual demand *X* after the emergency; the fifth part is the expected profit obtained by enterprises selling the supplies produced by transformation according to the agreement when the actual demand *X* is more than the sum of the physical reserve Q_{g3} and the enterprise production capacity reserve Q_{s1}.

Comparing the joint reserve mode with the state's physical reserve mode, the change of the state's expected cost is as follows:

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$$\Delta E_C = E_{C2} - E_{C1}$$
$$= (P_1 + H - P_3)\left(Q_{g3} - Q_{g1}\right) + (T + P_2 - P_3)Q_{s1}$$
$$+\omega \int_{Q_{g3}}^{Q_{g1}} F(X)\, dX + P_3 \int_{Q_{g1}}^{Q_{s1}+Q_{g3}} F(X)\, dX - P_2 \int_{Q_{g3}}^{Q_{s1}+Q_{g3}} F(X)\ dX \quad (10)$$

The change of enterprise's expected profit is:

$$\Delta E_W = E_{W2} - E_{W1}$$
$$= (P_1 - C)(Q_{g3} - Q_{g1}) + (T - N + P_2 - C)Q_{s1}$$
$$-(P_2 - C) \int_{Q_{g3}}^{Q_{g3}+Q_{s1}} F(X)\, dX \quad (11)$$

The expected profit of overall benefit is:

$$E_{Z2} = E_{W2} - E_{c2}$$
$$= (P_3 - C - H)Q_{g3} + (P_3 - N - C)Q_{g3} - P_3 M$$
$$+C \int_{Q_{g3}}^{Q_{g3}+Q_{s1}} F(X)\, dX\omega \int_0^{Q_{g2}} F(X)\, dX + P_3 \int_{Q_{g3}+Q_{s1}}^{M} F(X)dX \quad (12)$$

(3) Determination of optimal physical reserve, production capacity reserve and subsidy

The goal of joint reserve decision-making is to minimize the cost of supplies reserve, increase the enterprise profit and maximize the overall benefit as much as possible, on the premise that the quantity of emergency supplies provided can guarantee the supply needs of emergencies. It can be seen from equation (12) that the overall benefit depends on the state's cost and the enterprise's profit. To maximize the overall benefit, it is necessary to minimize the state's cost and maximize the enterprise's profit. Among it, the state's cost are influenced by such factors as physical reserve, subsidies provided to the society, physical price, management fee for physical reserve, etc. The enterprise's profit is influenced by such factors as production capacity reserve, production cost, subsidies provided by the state, selling prices of physical supplies, etc. Among the influencing factors, only physical reserves, production capacity reserves and subsidies provided by the state to enterprises can be jointly controlled and determined by both the state and enterprises in decision-making, while other factors can only be determined by the decision-making party, or even cannot be controlled and determined. Therefore, only by determining the supplies reserve, production capacity reserve and the optimal subsidies provided by the state to enterprises can the overall benefit of decision-making be maximized.

Under the joint reserve mode, the basic guarantee level of emergency supplies should not be lower than the basic guarantee level under the condition that the state only reserves in kind. That is, the total reserve of emergency supplies should not be less than that under the condition that the state only reserves in kind. Thus, the reserve of emergency supplies at this time should meet the necessary conditions: the sum of the optimal state's physical reserve and the optimal enterprise' production capacity reserve under the joint

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reserve mode should be equal to the state's physical reserve, which is expressed as follows:

$$Q_{g3} + Q_{s1} = Q_{g2} \tag{13}$$

Determination of the optimal state's physical reserve and the optimal enterprise' production capacity reserve. After substituting equation (13) into equation (8), it is simplified as follows:

$$E_{C2} = (P_1 + H - T - P_2)Q_{g3} + (T + P_2 - P_3)Q_{g2} + P_3 M \\ -\omega \int_0^{Q_{g3}} F(X)dX \; - \; P_2 \int_{Q_{g3}}^{Q_{g2}} F(X)dX - P_3 \int_{Q_{g2}}^{w} F(X)dX \tag{14}$$

Derivation analysis of equation (14) shows that if there is Q_{g3}, E_{C2} has the minimum value. That is, there is Q_{g3}corresponding to $\frac{\partial E_{C2}}{\partial Q_{g3}}$ =0. According to the zero point theorem, if $min_{Q_{g3}\to 0}\frac{\partial E_{C2}}{\partial Q_{g3}} < 0$ and $min_{Q_{g3}\to w}\frac{\partial E_{C2}}{\partial Q_{g3}} > 0$ are to be satisfied, then $P_1 + H - P_2 \leq T \leq P_1 + H - \omega$. Letting$\frac{\partial E_{C2}}{\partial Q_{g3}}$ =0, we can find out the physical reservewhen the state spends the least in the joint reserve mode as follows:

$$Q'_{g3} = F^{-1}(\frac{P_2+T-P_1-H}{P_2-\omega}), P_1 + H - P_2 \leq T \leq P_1 + H - \omega \tag{15}$$

It can be seen from equation (13)

$$Q'_{g3} \leq Q'_{g2} \Leftrightarrow F^{-1}(\frac{P_2+T-P_1-H}{P_2-\omega}) \leq F^{-1}(\frac{C+H-P_3}{\omega-P_3}) \Leftrightarrow \frac{P_2+T-P_1-H}{P_2-\omega} \leq \frac{C+H-P_3}{\omega-P_3} \tag{16}$$

Thus

$$Q_{g3} = \begin{cases} Q'_{g3}, & P_1 + H - P_2 \leq T \leq P_1 + H - \omega \; and \; \frac{P_2+T-P_1-H}{P_2-\omega} \leq \frac{C+H-P_3}{\omega-P_3} \\ Q'_{g2}, & Other \end{cases} \tag{17}$$

Derivation analysis of equation (9) is implemented in the same way. Letting $\frac{\partial E_{E2}}{\partial Qs_1}$ =0,the capacity reserve when the enterprise's profit is the largest under the joint reserve mode can be solved as follows:

$$Q'_{s1} = F^{-1}\left(\frac{T-N+P_2-C}{P_2-C}\right) - Q_{g3}, C + N - P_2 \; \leq T \leq N \tag{18}$$

Determination of the state's subsidies for enterprises. In the joint reserve decision-making, the subsidies provided by the state to enterprises is an important factor affecting the state's cost and the

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enterprise's profit. If both parties are willing to sign an agreement to participate in the joint reserve, then the subsidies provided by the state to enterprises should meet the following conditions:

$$\begin{cases} \Delta E_C = E_{C2} - E_{C1} < 0 \\ \Delta E_W = E_{W2} - E_{W1} > 0 \end{cases} \tag{19}$$

Based on equations (15), (16) and (18), the range of subsidies T provided by the state to enterprises is obtained as$T \in (T_{min}, T_{max})$, wherein

$$T_{min} = max\left\{\frac{(P_2 - C)\int_{Q_{g3}}^{Q_{g2}} F(X)\,dX - (P_2 - C)(Q_{g3} - Q_{g1})}{Q_{g2} - Q_{g3}} + N + C - P_2, P_1 + H - P_2, C - N - P_2, 0\right\}$$

$$T_{max} = min\left\{\frac{P_2\int_{Q_{g3}}^{Q_{g2}} F(X)\,dX - \omega\int_{Q_{g3}}^{Q_{g1}} F(X)\,dX - P_3\int_{Q_{g1}}^{Q_{g2}} F(X)\,dX + (P_1 + H - P_3)(Q_{g3} - Q_{g2})}{Q_{g2} - Q_{g3}}, P_1 + H - \omega, N, \left(\frac{C + H - P_3}{\omega - P_3}\right)(P_2 - \omega) + P_1 + H - P_2\right\}$$

Combining equations (13), (15) and (18), we can obtain:

$$Q'_{g3} + F^{-1}\left(\frac{T - N + P_2 - C}{P_2 - C}\right) - Q'_{g3} = F^{-1}\left(\frac{C + H - P_3}{\omega - P_3}\right) \Leftrightarrow F^{-1}\left(\frac{T - N + P_2 - C}{P_2 - C}\right) = F^{-1}\left(\frac{C + H - P_3}{\omega - P_3}\right) \tag{20}$$

From equation (20), it can be concluded that under the joint reserve mode, the best subsidies provided by the state to enterprises are:

$$T = \frac{(C + H - P_3)(P_2 - C)}{\omega - P_3} + C + N - P_2 \tag{21}$$

Ⅳ. CASE ANALYSIS

4.1 Case description and calculation results

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Taking the outbreak of COVID-19 epidemic in 2020 as an example, this paper analyzes the demand for medical protective clothing, determines the physical reserves, production capacity reserves and subsidies provided by the state to enterprises under the joint reserve mode, and analyzes the influence of prices and subsidies on decision-making, so as to provide suggestions for realistic decision-making.

The sudden outbreak of COVID-19 epidemic in January 2020 was a massive outbreak in China, causing enormous threat to people's lives and property and widespread impact. After the outbreak, there was urgent demand for medical emergency supplies, such as masks, disinfectant water, protective clothing, and respirators. The hospital shave long been unable to meet the actual demand for these supplies. Although China deployed all the medical supplies from the central and local reserves within a short period of time, and there was a large number of donations from the society, there was still a huge gap in the medical supplies needed by the hospitals nationwide. For example, the demand for medical protective clothing in Wuhan on February 6 was 59,900 pieces, but the gap rate was as high as 69%. During the epidemic, the contradiction between supply and demand of medical supplies in China has become increasingly prominent[19]. In terms of medical protective clothing, according to TABLE I, the Zhongshang Industry Research Institute has predicted that the daily demand for protective clothing in China can be as high as 1.9 million sets, but there are only 40 enterprises with production qualifications nationwide. As a special emergency material in anti-epidemic, the supply of medical protective clothing meeting the demand affects the anti-epidemic effect to a great extent. Moreover, its demand is large and the degree of its urgency is relatively high in the anti-epidemic process. Therefore, it is of great practical significance to study the reserve of medical protective clothing.

TABLE Ⅰ. Demand scale budget of China's protective clothing

Budget for demand scale of protective clothing in China	
Index	Data
Existing health technicians (10,000 people)	952.52
Assumed proportion of personnel engaged in	10%
Health technicians engaged in epidemic	95.3
Number of protective clothing consumed per	2
Value of single protective clothing (yuan)	120
Demand scale of protective clothing (100 million	162.39

Source: *Research Report on Market Investment Prospect of Medical Protective Clothing Industry in China in 2020* by Zhongshang Industry Research Institute.

Let the market price of medical protective clothing at the time of physical reserve by the state be 120 yuan per set and the agreed price with the enterprise be 150 yuan per set, the emergency purchase price be 200 yuan per set, the production cost of protective clothing be 60 yuan per set, the state's physical reserve management fee be 15 yuan per set, and the net salvage value of unused protective clothing be 55 yuan each set, the cost for the enterprise's production capacity reserve or product transformation preparation per unit quantity be 25 yuan. Let the demand for medical protective clothing obey a uniform distribution

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within [5000000, 7000000].

According to the above data, the distribution function number of demand within [5000000,700000] is

$$F(Y) = \begin{cases} \frac{X - 5000000}{2000000} \end{cases}$$

Then, the inverse function corresponding to the demand distribution function is

$$F^{-1}(X) = 2000000X + 5000000X \in [0,1]$$

Under the joint reserve mode combining the state's physical reserve and the enterprise's production capacity reserve, it can be known from equation (17) that the optimal physical reserve of medical protective clothing is

$$Q_{g3} = \begin{cases} Q'_{g3}, & P_1 + H - P_2 \le T \le P_1 + H - \omega \; and \; \frac{P_2 + T - P_1 - H}{P_2 - \omega} \le \frac{C + H - P_3}{\omega - P_3} \\ Q'_{g2}, & Other \end{cases}$$

Other $Q'_{g3} = F^{-1}(\frac{P_2+T-P_1-H}{P_2-\omega}), P_1 + H - P_2 \le T \le P_1 + H - \omega,$

$Q'_{g2} = F^{-1}(\frac{C+H-P_3}{\omega-P_3})$, $(P_3 > C + H > \omega)$

According to equation (18), the optimal production capacity reserve of medical protective clothing is

$Q'_{s1} = F^{-1}\left(\frac{T-c+P_2-C}{P_2-C}\right) - Q_{g3}, C - c - P_2 \le T \le c$

From equation (21), it can be seen that the optimal value of subsidies provided by the state to enterprises is

$T = \frac{(C+H-P_3)(P_2-C)}{\omega-P_3} + C + c - P_2, T \in (T_{min}, T_{max})$

Wherein

$$T_{min} = max\left\{\frac{(P_2 - C)\int_{Q_{g3}}^{Q_{g2}} F(X)\,dX - (P_2 - C)(Q_{g3} - Q_{g1})}{Q_{g2} - Q_{g3}} + c + C - P_2, P_1 + H - P_2, C - c - P_2, 0\right\}$$

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$$T_{max} = min\left\{\frac{P_2\int_{Q_{g3}}^{Q_{g2}} F(X)\,dX - \omega\int_{Q_{g3}}^{Q_{g1}} F(X)\,dX - P_3\int_{Q_{g1}}^{Q_{g2}} F(X)\,dX + (P_1 + H - P_3)(Q_{g3} - Q_{g2})}{Q_{g2} - Q_{g3}}, P_1 + H - \omega, N, \left(\frac{C + H - P_3}{\omega - P_3}\right)(P_2 - \omega) + P_1 + H - P_2\right\}$$

The decision-making results of two kinds of reserve modes, namely joint reserve and physical reserve are calculated by MATLAB and shown in TABLE Ⅱ. The relationship between physical reserve, reserve cost and enterprise profit in joint reserve mode is shown in Fig 4.

TABLE II Results of case decision-making by joint reserve model and physical reserve model

	Joint reserve	**Physical reserve**	
Reserve cost	1,183,391,091 yuan	11,896,120,969yuan	Reduced by 6,220,978 yuan
Enterprise profit	364,260,163 yuan	353,793,103yuan	Increased by 10,467,060 yuan
Total reserve	6,724,138 pieces	5,896,522pieces	Increasedby827,586 pieces
Physical reserve	5,580,762pieces	5,896,552pieces	Decreasedby315,790 pieces
Production capacity reserve	1,143,376pieces		
Subsidy	12.6 yuan		

The results in TABLE II show that, compared with the traditional supplies reserve model, the joint reserve model has the advantages of improving the emergency support rate, reducing the reserve cost and increasing the enterprise profit.

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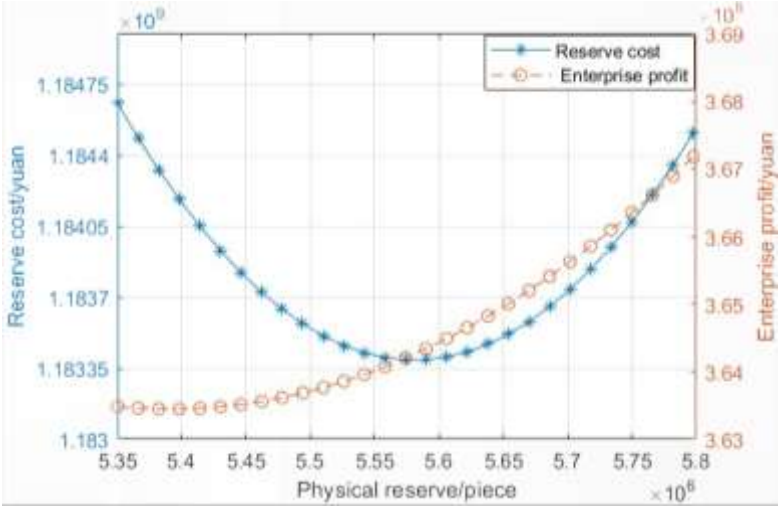

Fig 4: Changes of reserve cost and enterprise profit with physical reserve

4.2 Influence of parameter changes

(1) Influence of price changes

Other parameters are kept unchanged. The market price of medical protective clothing is changed from 110 yuan to 130 yuan, and the agreed price is changed from 140 yuan to 160 yuan, with the variation of 1 yuan. Then, the changes of physical reserve, production capacity reserve, expected reserve cost and expected enterprise profit caused by the change of market price and agreed price are shown in Fig 5 and 6:

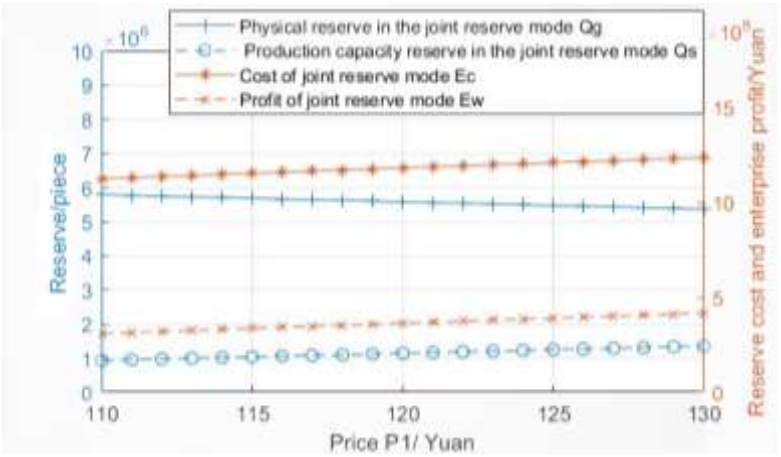

Fig 5: Influence of market price change on optimal reserve, reserve cost and enterprise profit

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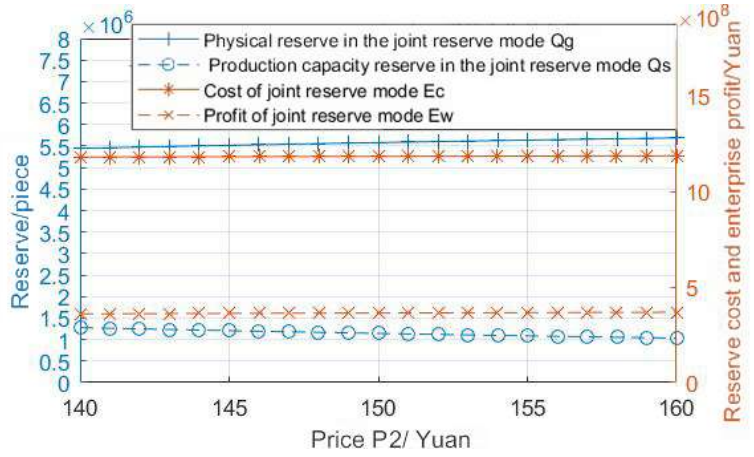

Fig 6: Influence of agreed price change on optimal reserve, reserve cost and enterprise profit

Compared with physical reserves, the changes in the decrease of physical reserves, the expected decrease of reserve cost and the expected increase of enterprise profit are shown in Fig 7 and 8.

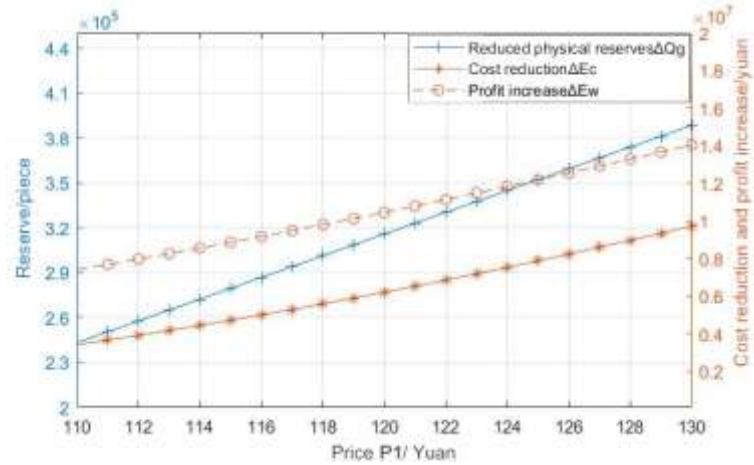

Fig 7: Influence of market price changes on changes of ΔQg, ΔE_C and ΔE_W

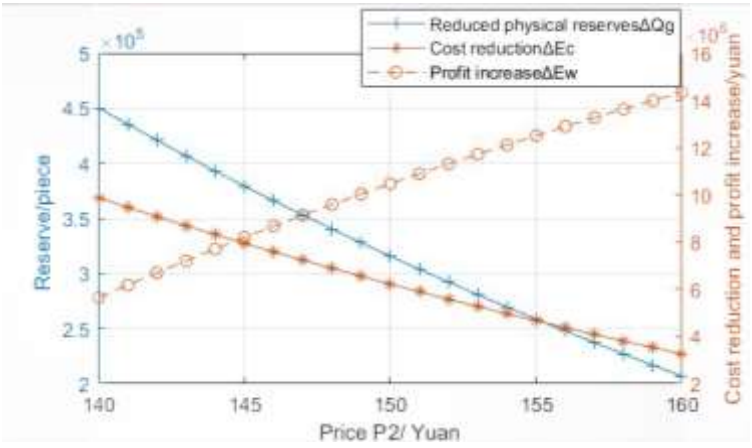

Fig 8: Influence of agreed price changes on changes of ΔQg, ΔE_C and ΔE_W

As can be seen from Fig 5 and Fig 6, with the increase of the market price of medical protective clothing, the optimal physical reserve is gradually decreasing, and the production capacity reserve is

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gradually increasing, but the opposite is true for the agreed price. Therefore, when the market price of supplies decreases or the agreed price increases, the supplies reserve cost can be reduced by increasing the physical reserve. Seen from Fig 7 and Fig 8, with the increase of market price of medical protective clothing, the joint reserve model plays an increasingly obvious role in reducing the physical reserve, reducing the cost of reserve and increasing the enterprise profit compared with physical reserves. With the increase of the agreed price, the effect of improving the enterprise profit becomes increasingly obvious, but the opposite is true for reducing the physical reserve and the reserve cost.

(2) Influence of subsidy changes

Other parameters are kept unchanged. The subsidy is changed from 5 yuan to 15 yuan, with the variation of 0.5 yuan. Then, the changes of physical reserve, production capacity reserve, expected reserve cost and expected enterprise profit with subsidies are shown in Fig 8. Compared with the physical reserve, the changes in the decrease of physical reserve, the expected decrease of reserve cost and the expected increase of enterprise profit are shown in Fig 9.

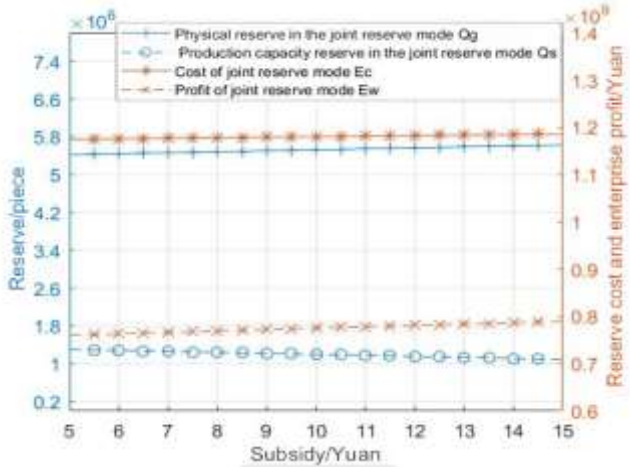

Fig 9: Influence of subsidy changes on optimal reserve, reserve cost and enterprise profit

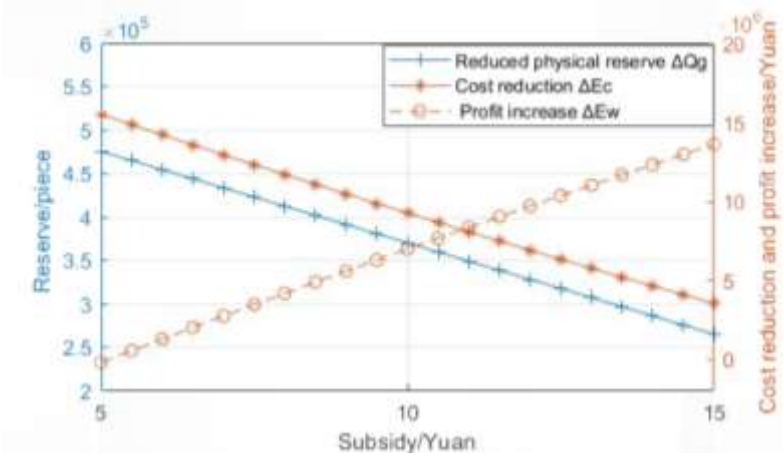

Fig 10: Influence of subsidy changes on ΔQg, ΔE_C and ΔE_W changes

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From Fig 10, with the increase of subsidies, the optimal physical reserve is gradually increasing, and the production capacity reserve is gradually decreasing. The reserve cost and enterprise profit are gradually increasing; compared with the physical reserve, the effect of increasing the enterprise profit is more obvious with the increase of subsidies, while the opposite is true for reducing the physical reserve and the reserve cost.

4.3 Decision-making suggestions

According to the calculation, the average growth rate of reserve cost and enterprise profit is 0.47% and 1.51% respectively when the market price is increased by 1 yuan; the average growth rate of reserve cost and enterprise profit is 0.03% and 0.12%, respectively when the agreed price is increased by 1 yuan; for each increase in subsidy by 0.5 yuan, the average growth rate of reserve cost is 0.05%, and the average growth rate of enterprise profit is 0.19%. Combined with the calculation results, and based on the influence of the above factors and possible problems in reality, the following suggestions for reserve decision-making are put forward:

(1) When the capital budget for reserve and the inventory capacity cannot be considered at the same time, the market price should be considered as the main factor when purchasing physical supplies. If the reserve funds are sufficient and the warehouse capacity is greatly limited, the purchase price of supplies in physical reserves can be increased in the process of joint reserve cooperation negotiation, because this can effectively increase the production capacity reserve and reduce the inventory capacity pressure of physical reserve. The opposite is true when the reserve funds are limited and the warehouse capacity is sufficient.

(2) To improve the willingness of enterprises to cooperate in joint reserve, we can increase the amount of subsidies, because the change of subsidies has little effect on the change rate of reserve cost under the joint reserve mode. But compared with the physical reserve mode, the increase of enterprise profit is more obvious. Therefore, in the negotiation of joint reserve cooperation, we should improve the willingness of enterprises to cooperate by increasing subsidies.

(3) For supplies with high requirement for timeliness, such as tents and beds, which are all put into use in a short time when an emergency occurs, the proportion of physical quantity should be increased in the supplies reserve to improve the supply support rate in the early stage of emergency treatment.

Ⅴ. Conclusion and prospect

5.1 Conclusion

Emergency supplies reserve is one of the necessary means to successfully and timely handle emergencies. Different emergencies have different requirements for required supplies. The supplies reserve model of using physical reserve for emergency supplies alone is not enough to get the maximum benefit in dealing with emergencies. In terms of quantity, type and structure, the physical reserve mode is difficult to

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www.forestchemicalsreview.com
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meet the demand of emergency materials for various types of emergencies. The use of joint reserve combining physical reserve and production capacity reserve of emergency supplies, to a certain extent, reduces the cost of physical reserve and increases the enterprise profit. Compared with physical reserve, it also reduces the physical reserve and increases the total reserve, thus improving the efficiency and saving reserve resources.

5.2 Outlook

This paper analyzes and discusses the shortcomings and the advantages of physical reserve and joint reserve, and uses the joint reserve model to determine the optimal physical reserve and production capacity reserve of medical protective clothing to effectively reduce the pressure of inventory capacity and the reserve cost and increase the enterprise profit. However, this paper has made many assumptions when discussing the problem, so there are still many shortcomings in this paper. Due to the time constraints, there are still the following problems requiring discussion and research.

(1) This paper assumes that the market price and agreed price of supplies are fixed, but emergency supplies reserve is an activity with a long time span, and material price changes are inevitable. Besides, the influence of material price changes and time value of funds on decision-making can be further studied.

(2) This paper lacks the consideration of the change of production cost caused by the change of raw material supply rate and raw material price in different periods. The demand for emergency supplies is also a simple probability assumption, which is difficult to determine in practice. So, we can also study the influence of the change of uncertainty probability on reserve decision-making.

(3) This paper only analyzes the specific emergency supplies when making decisions. The model in this paper has great restrictions on the varieties of supplies for decision-making, and cannot be applied to most common emergency supplies. Therefore, the model to reduce the restrictions on the varieties of supplies remains to be studied.

ACKNOWLEDGEMENTS

This research was supported by The 14th Five-Year Plan of Henan Education Science (Grant No.2021YB0172); Key Scientific Research Projects of Colleges and Universities in Henan Province (Grant No.19A413012).

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