Coordination Mechanism Design of Influenza Vaccine Supply Chain Under Uncertain Supply and Demand

Jie Wan[a], Sa Cui*

Hebei University of Technology, Tianjin China

[a]jeanwan1218@163.com; *cs18330296355@163.com

Abstract. This paper focuses on designing a coordinated model for a two-tier influenza vaccine supply chain system consisting of a manufacturer and a disease control center, considering uncertain supply and demand conditions to maximize influenza vaccine coverage. The design of the model considers three dimensions: order frequency (one-time and two-time), contract types (wholesale price contracts and option contracts), and decision-making modes (centralized and decentralized). The study begins with decentralized and centralized decision-making under a one-time ordering approach using wholesale price contracts, obtaining corresponding comparative parameters. It then proposes a coordinated approach using a combination of wholesale price contracts and option contracts under a two-time ordering approach, finding that under this approach, the manufacturer's optimal production input, the center for disease control and prevention (CDC)'s optimal order quantity, influenza vaccine coverage, and the profits of each member of the supply chain are all greater than those under the one-time ordering approach. Numerical analysis shows that: (1) combination contracts with adjustable option prices are beneficial for the reasonable distribution of profits among supply chain members, and (2) the impact of external demand and supply fluctuations on the two-time ordering approach is smaller than that on the one-time ordering approach. This paper demonstrates that the designed combination contract model under the two-time ordering approach can effectively coordinate the influenza vaccine supply chain system.

Keywords: Influenza vaccine supply chain· Portfolio contracts· two-ordering strategy· Supply chain coordination

1 Introduction

Influenza is a contagious disease that typically involves fever and vomiting, and in severe cases can lead to hospitalization or death. The most effective means of preventing and treating influenza is through influenza vaccination. However, there are uncertainties in the supply and demand of influenza vaccine. How to match the supply and demand of influenza vaccine is an urgent issue for members of the influenza vaccine supply chain. Duijzer et al[1]. consider the influenza vaccine supply chain to be divided into four stages: ingredient design, production, distribution, and distribution. In recent years,

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scholars at home and abroad have shifted their research focus to the issue of influenza vaccine supply chain design, focusing on the uncertainty of vaccine supply and demand, and reducing the uncertainty of influenza vaccine through contract design.

The demand for influenza vaccine is highly uncertain and unpredictable. Consumers who are vaccinated against influenza decide whether and when to be vaccinated, and this individual behavior is influenced by the external environment. Adida et al.[2] suggest that demand uncertainty arises from negative network effects, whereby some consumers choose to "free-rider" on the assumption that they are less likely to be infected as long as others are vaccinated. ". The 2019 neocoronavirus outbreak, with a 2.35-fold increased risk of in-hospital death in hospitalized patients co-infected with neocoronavirus and influenza compared to a single neocoronavirus infection, has led to an unprecedented increase in global influenza vaccine demand[3].

Uncertainty in the supply of influenza vaccine is due to uncertainty in the biological production process. Cho et al.[4] point out that the composition of the vaccine can have an impact on vaccine production, and that if the composition of the vaccine is not updated, the uncertainty in production can be lowered but the vaccine may be less effective, and if the composition is updated the vaccine's effectiveness can be increased but this may lead to higher supply uncertainty .Dai et al.[5] mention that the United States government decides on the composition of the vaccine in February-March each year, leaving little time for the production of vaccine, which makes it difficult to match supply with demand.

To address these problems, scholars at home and abroad have designed reasonable contract incentive mechanisms to reduce the uncertainty of supply and demand and improve the overall efficiency of the vaccine supply chain. The studies are divided into two types: primary ordering and secondary ordering, among which the subsidy contract to coordinate the vaccine supply chain by Chandra et al[6]. improved cost-sharing contract to motivate the manufacturers by Chick et al[7]. and the combined application of quantity flexibility contract and discount incentive by John et al[8]. With the development of science and technology, secondary ordering approaches have been proposed: Lin et al[9]. formalized a secondary ordering strategy for influenza vaccines and demonstrated that this strategy can improve the inefficiencies that exist in the influenza vaccine supply chain. Meanwhile, the secondary ordering method of influenza vaccine has been applied in practice: in 2021, the New South Wales government stipulated that after the successful delivery of a scheduled order of influenza vaccine, if the demand side still has unmet needs, a second order can be placed with the supply side[10]. However, existing research has not considered the coordination of the influenza vaccine supply chain with secondary ordering, nor has it considered whether secondary ordering can better cope with the impacts of changes in demand and supply, given changes in supply and demand.

2 Description of the Problem

In this paper, we consider a secondary influenza vaccine supply chain system consisting of a manufacturer and a CDC, with a Stackelberg game among the supply chain members. The CDC is the leader, and the primary ordering method is that the CDC predicts this year's demand based on last year's sales before the flu season arrives and orders flu vaccines from the manufacturer, who decides the amount of production to put in based on the amount of ordering from the CDC, and delivers the flu vaccines to the CDC before the arrival of the flu season, and then finally sells the flu vaccines to the CDC, and then finally discards the remaining flu vaccines. The second order method is that after the CDC receives the flu vaccine for the first time, it can order the flu vaccine from the manufacturer for a second time based on demand. The manufacturer delivers the flu vaccine to the CDC for the second time, and consumers who did not get vaccinated the first time can get the flu vaccine at this time, and then the remaining flu vaccine will be discarded.

3 Modeling and Solving

3.1 Assumptions and Variable Settings

The model constructed in this paper is based on the following assumptions:

Hypothesis 1: The flu vaccine is not completely effective;

Hypothesis 2: The overall probability of infection in the population is linear;

Hypothesis 3: Influenza vaccine penalty costs are less than influenza vaccine administration costs;

Hypothesis 4: The option price is less than the manufacturer's cost of production less than the strike price less than the wholesale price less than the option price + the strike price less than the CDC selling price;

The main variable symbols involved are shown in Table 1:

Table 1. Variable symbols and meanings

sign	hidden meaning	sign	hidden meaning
Q	Number of production inputs from manufacturers	m	Proportion of total production quantities put into production determined by the manufacturer based on CDC option quantities
C	Production cost per dose of influenza vaccine	Δ_y	Stochastic yield variation factors
P_r	Ordering cost per dose of influenza vaccine	U_y	Average value of production
P_a	Cost of administering each dose of influenza vaccine	Δ_x	Stochastic demand variation factors
N	Total population	U_x	average value of demand

W	Actual arrival of influenza vaccine	L_1	Manufacturer penalty costs
R_0	Basic infections	L_2	CDC Penalty Costs
f	Influenza vaccine orders	T(h)	Number of socially infected persons
f_1	First order of influenza vaccine	b	Total social infection costs
f_e	Second order of influenza vaccine	h	Effective influenza vaccine coverage
h	Influenza vaccine coverage	o	Option price per dose of influenza vaccine
β	Influenza vaccine effectiveness	e	Exercise price per dose of influenza vaccine

3.2 Modeling of a One-Time Ordering Method

3.2.1 Decentralized Decision Modeling

Decentralized decision-making refers to a decision-making approach in a supply chain system consisting of a manufacturer and a CDC that consider their own profits separately to achieve their own profit optimization. The supply chain is usually coordinated by signing a wholesale price contract. It is a common form in the current influenza vaccine supply chain.

The manufacturer's profit is shown in equation (1):

$$\pi^M(Q,\ f) = P_r fN - CQ - L_1[fN - YQ]^+ \tag{1}$$

The first term on the right side of the equation is the revenue generated by the CDC's order to the flu vaccine manufacturer, the second term is the cost of producing the flu vaccine, and the third term is the cost of the penalties that the CDC imposes on the manufacturer if it fails to deliver a sufficient amount of flu vaccine in a timely manner.

CDC's profits are affected by market conditions, and changes in the demand for influenza vaccine can affect influenza vaccine coverage and cause CDC's revenues to fluctuate. Referring to the calculation of Lin。, For influenza vaccine coverage, there are three scenarios：

Influenza vaccine coverage is shown in equation (2):

$$h = x \qquad x \le \min\left[f, \frac{yQ}{N}\right]; h = f \qquad f \le \min\left[x, \frac{yQ}{N}\right]; h = \frac{yQ}{N} \qquad \frac{yQ}{N} \le \min[x, f] \tag{2}$$

The profits of the CDC are directly related to the number of consumers who contract the flu. The cost of treatment, missed work, time, and medical care incurred by consumers who become infected with influenza constitutes the social cost of infection. The level of social infection costs has a direct impact on CDC profits. In order to calculate the cost of social infection, it is necessary to know the expected number of social infections. The number of social infections in this paper is cited in Chick's calculation as shown in Equation (3):

$$T(h)=0 \qquad h>\frac{R_0-1}{R_0\beta};T(h)\frac{R_0-1}{R_0} \qquad 0<h\le\frac{R_0-1}{R_0\beta} \tag{3}$$

From the above, you can derive the profit of the CDC as shown in equation (4):

$$\pi^R(Q,f)=(P+\alpha)E[(h)]-\mathrm{P_r}\,fN-WP_a-L2[fN-YQ]^+-bT(h) \tag{4}$$

The first term on the right side of the equation is the profit from the actual flu vaccine sold, the second term is the positive impact on society from those who have received the flu vaccine, the third term is the cost of ordering the flu vaccine, the fourth term is the cost of administering the flu vaccine, the fifth term is the cost of penalties given to the CDC by the market if the flu vaccine is not delivered in a timely manner, and the sixth term is the cost of social infections.

Proposition 1: The manufacturer's optimal input production quantity Q^M is the unique optimal solution for $\partial\pi^M(Q,\ \mathrm{f})/\partial Q$, and the optimal input production quantity Q for the manufacturer is a linear function: $Q^M(\mathrm{f})=fN/K^M, K^M=G^{-1}(c/L_1)$. Substituting the optimal input production quantity Q^{UM} of the manufacturer into $\pi^R(Q,\ \mathrm{f})$, we obtain the optimal ordering quantity f^R for the disease control center.

3.2.2 Centralised Decision-Making Model Construction

To provide a benchmark, we consider an ideal supply chain, i.e., the profitability of the supply chain when the CDC and the manufacturer make decisions centrally as a whole. The profit of the supply chain is shown in equation (5):

$$\pi^{SC}(Q,f)=\mathrm{PNE}\left(\frac{W}{N}\right)+\alpha NE\left(\frac{W}{N}\right)-cQ-WP_a-bT\left(\frac{W}{N}\right)-(L_1+L_2)[fN-YQ]^+ \tag{5}$$

The first term on the right side of the equation is the profit from the actual flu vaccine sold, the second term is the positive impact on society from the population that has been vaccinated, the third term is the cost of production of the flu vaccine, the fourth term is the cost of administering the flu vaccine, the fifth term is the cost of social infection, and the sixth term is the cost of penalties

Proposition 2: $\pi^{SC}(Q,\ \mathrm{f})$ is jointly concave for Q and f, i.e., there exist optimal solutions of $\pi^{SC}(Q,\ \mathrm{f})$ for Q^{SC}, f^{SC}.

3.3 Decentralized Vs Centralized Models

Lemma 1: The ratio of the optimal number of influenza vaccines to be ordered and the optimal amount to be put into production in the decentralized decision is greater than the ratio of the optimal number of influenza vaccines to be ordered and the optimal amount to be put into production in the centralized decision, i.e: $f^R N / Q^M(f^R) > f^{SC} N / Q^{SC}(f^{SC})$

Lemma 1 states that centralized decision-making on the optimal number of influenza vaccines to be ordered can provide more production incentives for manufacturers, which in turn can alleviate the shortage of influenza vaccines due to insufficient production of influenza vaccines.

Lemma 2: (i) Influenza vaccine coverage is greater under centralised decision-making than under decentralised decision-making $E[h]_{SC} \geq E[h]_{M-R}$.

((ii) Manufacturer inputs and CDC orders are greater under centralised decision-making than under decentralised decision-making $Q^{SC} \succ Q^M ; f^{SC} \succ f^R$.

Lemma 2 (i) states that effective influenza vaccine coverage is greater under centralized decision-making than under decentralized decision-making. (ii) shows that the number of units produced by a manufacturer under centralized decision-making is greater than the number of units produced by a manufacturer under decentralized decision-making. Therefore, this paper designs a secondary ordering method and uses a combination of option contracts and wholesale price contracts to coordinate the influenza vaccine supply chain.

3.4 Model Construction under the Secondary Ordering Method

3.4.1 Decentralized Decision Modeling

The influenza vaccine is ordered in two orders under the secondary ordering method, and the CDC profit is divided into two parts based on the number of times the influenza vaccine is ordered: the first part is the cost incurred for the first order of the influenza vaccine; and the second part is the cost incurred for the second order of the influenza vaccine, the total sales revenues, and the cost of the social infections. The first part of the profit is shown in equation (6):

$$\pi_1^{UR}(Q, \ \mathrm{f}) = -\mathrm{P}_{\mathrm{r}} f_1 N - WP_a - L_2\left[f_1 N - y(1-m)Q\right]^+ \tag{6}$$

The first is the cost of ordering the flu vaccine for the first time; the second is the cost of administering the flu vaccine; and the third is the cost of penalties given to the CDC by the market if the flu vaccine is not delivered in a timely manner;

The second component consists of social infection costs and total sales revenue, both of which are related to influenza vaccine coverage. The CDC orders influenza vaccine twice under the secondary ordering method, so the influenza vaccine coverage rate changes compared to the primary ordering method, and the expectation of influenza vaccine coverage rate under the secondary ordering method is shown in Equation (7):

$$E\left[h^U\right]=\begin{cases}\int_0^{f_1+f_e} x d\Phi(x)+\int_{f_1+f_e}^{U_x+\Delta_x}(f_1+f_e)d\Phi(x) & f_1N\le y(1-m)Q\\ \int_0^{\frac{y(1-m)Q}{N}+f_e} x d\Phi(x)+\int_{\frac{y(1-m)Q}{N}+f_e}^{U_x+\Delta_x}\left(\frac{y(1-m)Q}{N}+f_e\right)d\Phi(x) & f_1N\ge y(1-m)Q\end{cases} \tag{7}$$

The second part of the profit is shown in equation (8):

$$\pi_2^{UR}(Q,f)=-oQ_o-(e+P_a)f_eN-bM+\left(b+(P+\alpha)N\right)E\left(h^U\right) \tag{8}$$

The first term on the right side of the equation is the profit earned from the sale of the CDC's flu vaccine; the second term is the positive societal impact of the population that has received the flu vaccine; and the third term is the cost of the CDC's option to place a second order for the flu vaccine. The fourth term is the cost of exercising the option for the second order; the fifth term is the cost of administering the flu vaccine for the second order; and the sixth term is the cost of social infection.
The manufacturer's profit under the secondary ordering method is shown in equation (10):

$$\pi^{UM}(Q,f)=(mo-c)Q+\mathrm{P_r} f_1N-L_1\left[f_1N-y(1-m)Q\right]^{+}+eN\left[\int_{\frac{f_1N}{(1-m)Q}}^{U_y+\Delta_y} f_e^{*}dG(y)\int_0^{\frac{f_1N}{(1-m)Q}} f_e^{**}dG(y)\right] \tag{9}$$

The first term on the right-hand side of the equation is the cost of input production; the second term is the profit from the first sale of flu vaccine, the third term is the cost of penalties for failure to deliver the flu vaccine on time; and the fourth term is the revenue from the second sale of flu vaccine.

Lemma 3: Substituting f_e^* and f_e^{**} into $\pi^{UM}(Q,f)$, there exists Q^{UM} such that $\pi^{UM}(Q,f)$ is optimal.

The profit of the disease control center under the two-time ordering scheme is composed of two parts, as shown in Formula (9).

$$\begin{aligned}\pi^{UR}(Q,f)=(P+\alpha)NE\left(h^U\right)-\mathrm{P_r} f_1N-WP_a-\\ L_2\left[f_1N-y(1-m)Q\right]+-bT\left(h^U\right)-omQ-ef_eN\end{aligned} \tag{10}$$

Lemma 4: By substituting f_e^*, f_e^{**}, and Q^{UM} into $\pi^{UR}(Q,f)$, there exists f_1^{UR} that maximizes $\pi^{UR}(Q,f)$.

3.4.2 Centralized Decision Model for Primary Ordering vs. Decentralized Decision Model for Secondary Ordering

Proposition 4: The quantity of influenza vaccine ordered by the CDC and the quantity put into production by the manufacturer under the secondary ordering combination contract is greater than the result of the primary ordering wholesale price contract. $f^{SC} \prec f_1^{UR}$, $Q^{SC} \prec Q^{UM}$.

Proposition 4 $f^{SC} \prec f_1^{UR}$ Indicates that the optimal order quantity in the primary ordering method is less than the first optimal order quantity for secondary ordering of influenza vaccine. $Q^{SC} \prec Q^{UM}$ Indicates that the manufacturer's production quantity under the secondary ordering method is greater than the manufacturer's production quantity under the primary ordering method.

Lemma 6: Influenza vaccine coverage under the secondary ordering method is greater than the centralized decision-making influenza vaccine coverage under the primary ordering method, i.e:$E[h]_{UM-UR} > E[h]_{SC}$.

Lemma 6 indicates that the secondary ordering method is better than the primary ordering method in coordinating the supply chain.

4 Numerical Experiments

The range of values of the basic parameters of the numerical experiment is shown in Table 2:

Table 2. Parameter value range

parameters	Parameter range	parameters	Parameter range
m	[0.25 – 0.4]	R_0	[1.5 – 2.5]
c	5	f_1	0.40
e	[6 – 9]	f_e	0.10
o	4	f	0.37
P_r	[10 – 15]	Q^M	0.5
P_a	[5 – 12]	Q^{UM}	0.7
L	15	β	[0.65 – 0.95]
$\triangle_X$	[0.4 – 0.7]	$\triangle_Y$	[0.95 – 1.05]

4.1 Impact of Fluctuations in Supply and Demand

This section considers the impact of supply and demand changes on supply chain decisions, as shown in Figure 1:

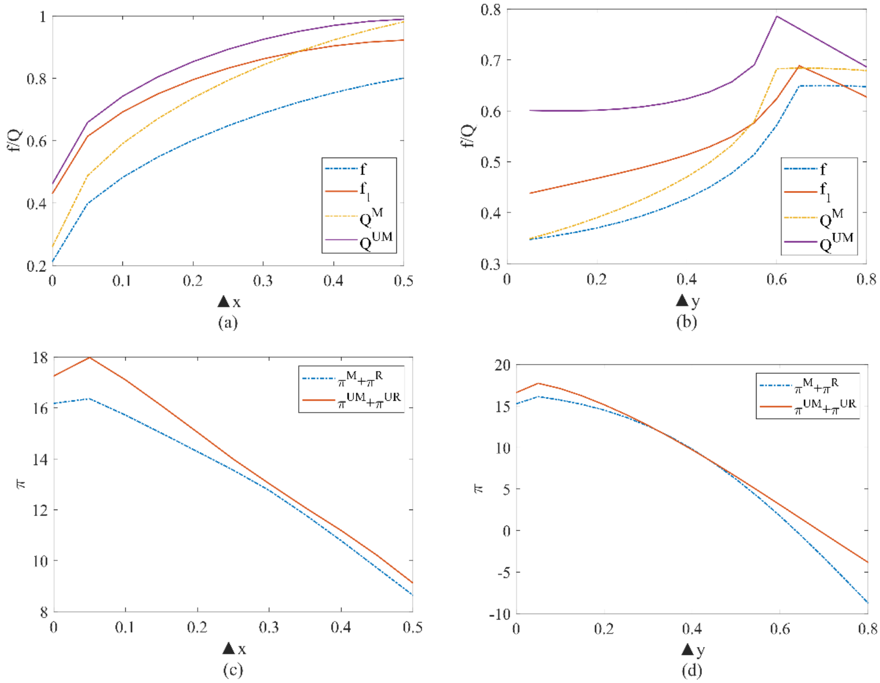

Fig. 1. Impact of fluctuations in demand or supply

Figure 1(a) indicates that when demand fluctuations are small, both ordering methods choose to increase the quantity ordered and the amount of input production. When demand fluctuations are increasing, the secondary ordering method has a flatter rise in CDC order quantity and manufacturer input production, which can mitigate the shock of demand uncertainty. Figure 1(b) indicates that the manufacturer's influenza vaccine input production is always greater than the CDC's influenza vaccine order quantity, and when supply fluctuates to a certain threshold, the primary ordering method does not increase the order quantity and input production. The secondary ordering method chooses to reduce the ordering and production inputs in response to changes in supply fluctuations. Figure 1(c) shows that when the demand fluctuation is small, the sum of profits of supply chain members firstly shows a slow rising trend, but as the demand fluctuation gradually increases, the sum of profits of supply chain members decreases sharply, but the sum of profits of supply chain members under the secondary ordering method decreases more slowly. However, the sum of profits of supply chain members decreases slower under the secondary ordering method. Figure 1(d) shows that when the supply fluctuation is small, the sum of supply chain profits first shows a slow upward trend, but as the supply fluctuation gradually increases, the slope of the decrease of the sum of supply chain members' profits in the primary ordering method is from small to large, and the slope of the decrease of the sum of supply chain members' profits in the secondary ordering method is from large to small, which indicates that the secondary ordering method is able to better withstand the impacts of the fluctuation changes and the sum of supply chain members' profits is greater than the sum of supply chain members' profits in the primary ordering method under the secondary ordering method.

5 Conclusion

In this paper, a secondary influenza vaccine supply chain system consisting of a manufacturer and a CDC is taken as the object of study in the context of uncertain supply and demand of influenza vaccine, and the study compares the input production volume of the manufacturer, the ordering volume of the CDC, and the coverage of influenza vaccine under the primary ordering method and the secondary ordering method. Firstly, a primary ordering model is developed under different decision-making environments and the optimal solution is found; secondly, a secondary ordering model is developed by introducing the secondary ordering method to find out the optimal solution and compare it with the primary model; finally, numerical analyses are conducted to validate the relevant conclusions and derive some management insights. The research results show that:

(1) In the context of supply and demand uncertainty, both the manufacturer and the CDC increase their profits in the secondary ordering approach compared to the primary ordering approach.

(2) Under the primary ordering method, the wholesale price contract cannot coordinate the influenza vaccine supply chain, while the combination of the wholesale price contract and the option contract under the secondary ordering method can better coordinate the influenza vaccine supply chain.

(3) When demand and supply fluctuate, the influenza vaccine supply chain under the secondary ordering method is more resilient to shocks caused by fluctuations in demand and supply than the primary ordering method.

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