TWO STUDIES ON IMPROVING THE EFFICIENCY OF VACCINE SUPPLY CHAIN

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Two Studies on Improving the Efficiency of Vaccine Supply Chain

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CERTIFICATE OF ORIGINALITY

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Abstract

Worldwide, annual epidemic like influenza results in millions severe illnesses. However, the coverage of vaccine, which is the most effective way to prevent infections, is undesirably low. The vaccination coverage changes every flu-season, and is determined by the minimum of supply and demand. Previous research on vaccination coverage mainly focuses on single-period models and the supply shortage. In this thesis, we study the vaccine supply chain under multi-period models, where we denote each period as one flu season for simplicity, and explore the demand uncertainty. We conduct two studies on the inefficiency of a vaccine supply chain, i.e., the low vaccination coverage, taking account of multi-period vaccine market and consumer vaccination regret, respectively.

In the first study, we construct a multi-period vaccine demand model to study multi-period vaccine supply decisions and government interventions. We assume that members of the public make vaccination decisions at the beginning of a flu season, given the situation of the last flu season. Both the manufacturer and government will make multi-period decisions. We formulate the problem, characterize the solution properties, and derive the multi-period profit-maximizing coverage and multi-period socially optimal coverage. In addition, we show that, besides supply uncertainty, vaccine demand decreases or increases with the vaccination coverage in the last flu season, depending on vaccine effectiveness. Furthermore, the coverage convergence depends on vaccine effectiveness and infection cost distribution. Accordingly, the multi-period profit-maximizing coverage and multi-period socially optimal coverage depend on the vaccine effectiveness and coverage convergence. We also conduct numerical experiments to generate practical implications of the analytical findings. Our results provide management insights on vaccine supply decisions, government

interventions and vaccination coverage.

In the second study, we formulate a single-period vaccine demand model incorporating the free rider behavior and customer regret. Solving the model, we show that, as the coefficient of customer regret increases, more people would like to be free riders, which affects the vaccine market coordination. When the coefficient of customer regret is large enough, there will be no risk-taking customers under the socially optimal vaccination coverage. Extending the model to include incomplete demand information and oligopolistic supply, we find that both inaccurate estimation of customer regret and incomplete supply competition will lead to imbalance of supply and demand. Finally, considering government's subsidy allocations on both supply and demand sides, we present a subsidy allocation mechanism to help the market achieve the largest equilibrium coverage.

Publications Arising from the Thesis

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Chapter 1

Introduction

Vaccination is the most effective way to prevent people from being infected by infectious diseases. Every year millions of people take preventive vaccination before an infectious disease emerges. Vaccine supply chain is an indispensable part of successful vaccination campaigns.

The success of a vaccine supply chain, which an important part of healthcare management, depends on individuals' vaccination behaviors and manufacturer's production decisions. With the observation of vaccine market, the government can intervene the supply side and the demand side to improve the vaccination coverage to a socially optimal level. Considering vaccine supply chain with government interventions, we conduct two studies, regarding multi-period vaccine market and consumer regrets of vaccination. Our aim is to find the inefficiency of the vaccine supply chain, and help the government intervene the vaccine market more efficiently.

First, people have different vaccination habits and vaccine demand changes in every flu season. People make vaccination decisions around the beginning of a flu season period, when they do not have the infection information of this period. Thus, it is necessary to study individuals' vaccination decisions in a multi-period setting and improve the efficiency of vaccine market under a multi-period situation.

In Chapter 2, we construct a multi-period vaccine demand model to study multi-period vaccine supply decisions and government interventions. We assume that members of the public make vaccination decisions at the beginning of the flu season, given the situation of the last flu season. Both the manufacturer and government will make multi-period decisions. The vaccination coverage is determined by the minimum of supply and demand. We formulate the problem, characterize the solution properties, and derive the multi-period profit-maximizing coverage and multi-period socially optimal coverage. In addition, we show that, besides supply uncertainty, vaccine demand decreases or increases with the vaccination coverage in the last flu season, depending on vaccine effectiveness. Furthermore, the coverage convergence depends on vaccine effectiveness and infection cost distribution. Accordingly, the multi-period profit-maximizing coverage and multi-period socially optimal coverage depend on the vaccine effectiveness and coverage convergence. We also conduct numerical experiments to generate practical implications of the analytical findings. Our results provide management insights on vaccine supply decisions, government interventions and vaccination coverage.

Second, the imperfection of vaccine and herd immunity result in the situation where vaccinated individuals can be infected and non-vaccinated individuals might be healthy. Those non-vaccinated and healthy people benefit from free-riding behavior. It is envisaged that the free-riding behavior is a main cause of the low vaccination coverage and affected by customer regret. Customers' vaccination decisions made under uncertainty will lead to regret ex post. To the best of our knowledge, no research has addressed this issue.

In Chapter 3, we consider customer regret in the vaccination demand model when formulating customers' free-riding behavior. In our model, regret is related to the coefficient of regret and proportional to the difference between the customers' actual utility and the best utility of the alternative choices. Our study is different from those in the literature in that we do not impose a positive restriction on regret, because we believe that when a person finds the utility of his choice is better than the utility of all the alternative choices, he will feel happy or be proud of his choice. We use negative regret to represent this kind of feeling. In this model, the coefficient of regret affects the proportion of individuals that insist on being free riders. When the coefficient of regret is large enough, we find that the socially optimal vaccination coverage does not encourage individuals to be risk-taking customers anymore. Our study also examines government's subsidy allocations on both the supply and demand sides with consideration of customer regret. Our mechanism could help the market to achieve the largest equilibrium coverage, which is applicable even when the government's budget is limited.

Chapter 2

Vaccine Supply Decisions and Government Interventions under Multi-period Demands

2.1 Introduction

Humans are plagued by infectious diseases, like influenza, perennially. Serious outcomes of influenza infection can result in hospitalization or even death. The most effective way to prevent influenza infection is by receiving vaccination every year (CDC 2019). But vaccination coverage is always undesirably low and below the socially optimal level (Blue 2008). On the supply side, supply shortage contributes to the low level of vaccination coverage, where production uncertainty is an important characteristic of the vaccine production process (via embryonated chicken eggs). On the demand side, the *positive externality effect*, i.e., vaccination not only protects the vaccinated people, but also decreases the infection probability of the non-vaccinated people by decreasing their contacts with the infected people, results in low vaccine demand and low vaccination coverage (Fine et al. 2011, Gordis 2013). So the efficiency of the vaccine supply chain, i.e., vaccination coverage, needs to be studied and improved.

Many researchers have studied the vaccine supply chain in the single-period setting, where we set each period as one flu season in this thesis. For example, Chick et al. (2008) and Deo and Corbett (2009) study the production efficiency of the vaccine manufacturer. Bauch and Earn (2004), Reluga et al. (2006) and Vietri et al.

(2008) show that consumers make their own vaccination decisions based on the infection probability and their own infection costs, which leads to insufficient demand. Mamani et al. (2012) and Arifoğlu et al. (2012) analyze government interventions to minimize the total social cost. However, in real practice, people might not make the same decision in each period and do not know the real-time infection probability. Thus, it is necessary to study the efficiency of the vaccine supply chain in multi-period setting.

The characteristics of the vaccine supply chain in the multi-period setting are as follows: First, people have different vaccination habits and vaccine demand changes in every flu season. Myopic consumers may be afraid of being infected while free-riding consumers insist to be free riders. In addition, strategic consumers make different decisions in each flu season based on the infection probability. Second, vaccine demand is usually at its peak in October or November, and rapidly declines afterwards (CDC 2018). So people make vaccination decisions around the beginning of a flu season (period), when they do not have the infection information about the current period. Third, due to the long production process (six to eight months for influenza vaccines), the manufacturer makes the production decision far ahead of the flu season. The manufacturer would seek to maximize its profit and avoid the overstock risk. The government also intervenes in the vaccine market in each period seeking to increase vaccine coverage in the community.

Motivated by the above observations, we study in this chapter the vaccine supply decisions and government interventions in the multi-period setting. We set out to address the following research questions: How do people make vaccination decisions? How does vaccination externality affect people's decisions? How should the manufacturer and the government more efficiently make production decisions and intervene in the market, respectively?

To answer the above research questions, we develop a multi-period vaccine supply chain model, in which people make decisions in each flu season based on the situation in the last flu season. All people make decisions at the beginning of a flu season at the same time, and have no idea of the others' choices in the current season. We integrate consumers' rational decisions with their vaccination habits. We consider three types of consumers, namely myopic consumers, who receive vaccination under all circumstances; free-riding consumers, who receive vaccination under no circumstances; and strategic consumers, who strategically make their vaccination decisions. As such, the demands among the periods are related. For the decisions of the manufacturer and the government, we first study a two-period model and then extend it to a multi-period model. The manufacturer decides its production quantity over two or an infinite number of periods to maximize its expected total profit, under the assumption that the manufacturer knows the multi-period demand relations. The government seeks to minimize the total social cost, comprising consumers' utility and the manufacturer's profit. We also study the multi-period socially optimal coverage in comparison with the demand convergence.

We find that the among-period demand relations are based on vaccine effectiveness. The Australian government reports that influenza vaccine effectiveness is between 30 and 60 per cent (AGDH 2018). While the basic reproduction number for influenza is two to three (Wikipedia 2018), the critical fraction, i.e., the minimum level of vaccination coverage necessary for providing herd immunity, can be higher than or lower than one. If vaccine effectiveness is high enough to make the critical fraction less than one, vaccine demand decreases with the coverage in the last period. This result is due to the multi-period positive externality effect. We set the coverage that makes the demands in following periods unchanged as the convergence value. For the manufacturer, the two-period profit-maximizing coverage increases with the actual production in the first period and decreases with the actual production in the second period. For the government, the two-period and one-period socially optimal coverages are on the same side of the coverage convergence value, and the two-period socially optimal coverage is always closer to the coverage convergence value. If vaccine effectiveness is lower and makes the critical fraction larger than one, vaccine demand increases with the coverage in the last period. In this situation, vaccines cannot provide effective protection for the vaccinated and the in-direct protection for the non-vaccinated is also negligible. Then more and more people choose to receive vaccination to avoid a high infection cost. For the manufacturer, the two-period profit-maximizing coverage is always the highest demand and is not influenced by production uncertainty.

The coverage convergence in a free market without government interventions depends on vaccine effectiveness and infection cost distribution. We divide the situations into six types according to the infection cost distribution. If the critical fraction is less than one, the coverage follows an alternating sequence around the convergence value. For the manufacturer, the multi-period profit-maximizing coverage depends on the infection cost distribution and is on the same side of the convergence value for the two-period profit-maximizing coverage. When the fluctuation of the alternating sequence decreases, the multi-period profit-maximizing coverage is farther away from the convergence value. In contrast, when the fluctuation increases, the multi-period profit-maximizing coverage is closer to the convergence value. For the government, when the fluctuation of the alternating sequence decreases, the multi-period socially optimal coverage is on the same side of the convergence value for the two-period socially optimal coverage. When the fluctuation increases, the multi-period and two-period socially optimal coverages are in the same interval. If the critical fraction is greater than one, the coverage might converge to the lowest demand, the highest demand, or keep the value of the first period. For the manufacturer, the multi-period profit-maximizing coverage is always the highest demand and does not change with production uncertainty.

We organize the rest of the paper as follows: In Section 2.2 we review the related literature. In Section 2.3 we introduce the key elements of the model, covering the demand, supply, and epidemiology aspects. In Section 2.4 we present a two-period vaccine supply chain model, while in Section 2.5 we extend it to a multi-period model. In Section 2.6 we conclude the paper and suggest topics for future research. We present all the proofs in Appendix A.

2.2 Literature Review

The efficiency of the vaccine supply chain, which is influenced by supply and demand, has drawn much attention from operations management researchers (Chick et al. 2008, Deo and Corbett 2009, Cho 2010, Arifoğlu et al. 2012, Mamani et al. 2013). Production uncertainty and insufficient production incentives for the manufacturer are the main causes of supply shortage. Chick et al. (2008) study several types of contracts with the objective of maximizing the benefits of the government and the manufacturer at the same time. Deo and Corbett (2009) find that yield uncertainty results from the industry concentration and output reduction. Wu et al. (2005) and Cho (2010) propose that dynamic supply decisions can improve the social benefit. On the demand side, positive vaccination externality is a main cause of insufficient vaccine demand. Several studies (Bauch and Earn 2004, Reluga et al. 2006) analyze the vaccine demand market using game theoretic models. Considering production uncertainty, Arifoğlu et al. (2012) study the impact of inefficiency on both the supply and demand sides. Most of these studies develop models in the single-period setting. In contrast, we construct a multi-period vaccine demand model to study multi-period vaccine supply decisions and government interventions.

Vaccination externality resulting from herd immunity influences strategic consumers' behaviour (Brito et al. 1991, Boulier et al. 2007, Cook et al. 2009, Arifoğlu et al. 2012, and Tereyağoğlu and Veeraraghavan 2012). Dana and Petruzzi (2001) assume that consumers are utility maximizing. Boulier et al.(2007) empirically illustrate that the magnitude of vaccine externality is influenced by the efficacy of vaccination. Chapman and Coups (1999) propose that vaccination acceptance is related to whether consumers have received vaccination in the previous year. Vaccination externality also has different effects on people with different vaccination habits. Aviv and Pazgal (2008) and Su and Zhang (2008) study the influence of forward-looking consumer behaviour. Cachon and Swinney (2009) introduce three types of consumers to analyze consumers' strategic behaviour, including myopic consumers, bargain-hunting consumers, and strategic consumers. MacDonald et al. (2015) consider some people who accept all vaccines and some people who refuse all vaccines in their study of vaccine hesitancy. To the best of our knowledge, we are the first to develop a multi-period vaccine demand model that incorporates vaccination externality into people's vaccination habits to study the vaccine supply chain. We show that, due to vaccination externality, consumers' vaccination decisions depend on their vaccination habits and vaccine effectiveness.

With among-period demand relations, the multi-period socially optimal coverage for the government is different from its single-period counterpart. Brito et al. (1991), Geoffard and Philipson (1997), and Philipson (2000) consider the health economic issues arising from vaccination and find that the vaccination coverage is below the socially optimal level. Mamani et al. (2012) consider the costs and benefits of general customers, as well as vaccine producers, to derive the total social surplus. Arifoğlu et al. (2012) analyze the inefficiency on the vaccine supply and demand sides, and highlight the interventions on both sides. They suggest that combining demand-side intervention (Brito et al. 1991) and supply-side intervention (Chick et al. 2008) could coordinate the entire supply chain. We study the socially optimal coverage in the multi-period setting for the government, which can improve the efficiency of government interventions.

2.3 Basic Model

In this section we discuss the basic assumptions and introduce the key elements of our model, covering the demand, supply, and epidemiology aspects.

2.3.1 Demand

Similar to Cachon and Swinney (2009) and MacDonald et al. (2015), we consider three types of consumers in our model, namely myopic consumers, who receive vaccination under all circumstances; free-riding consumers, who receive vaccination under no circumstances and want to benefit from being free riders; and strategic consumers, who strategically make their vaccination decisions. We set $\alpha \geq 0$ and $\beta \geq 0$ as the percentages of myopic consumers and free-riding consumers in the population, respectively. We assume that all the people have the same probability to be myopic consumers or free-riding consumers. This means that the probability distribution of the infection cost for the strategic consumers is the same as that for all the consumers. We further assume that α and β are constants in a certain population over several periods. Then the vaccination coverage in period t, denoted by f_t, is always in the interval $[\alpha, 1-\beta]$. Besides, the strategic consumers sometimes accept and sometimes refuse vaccines. They are self-interested and make decisions based on the vaccination costs and the possible infection costs (Vietri et al. 2008, Arifoğlu et al. 2012). In our multi-period model, all the people will make decisions at the beginning of each flu season at the same time. People do not have information as to whether other people will receive vaccination or not at the beginning of the flu season. So they can only make decisions based on the information about the last flu season, including the vaccination coverage and the related infection probability.

2.3.2 Supply

Most of injectable vaccines (over 97%) are produced from chicken egg embryos (Danzon et al. 2005, Palese 2006, Arifoğlu et al. 2012). Production uncertainty is one of the most important characteristics of the production method, which leads to serious inefficiency on the supply side of the vaccine supply chain (Mamani et al. 2012, Deo and Corbett 2009). Similar to the models developed by other researchers (Palese 2006, Chick et al. 2008, Deo and Corbett 2009), we set Y_t as the average production per egg in period t. Y_t varies among the periods and is within the interval $[0, +\infty)$ (Arifoğlu et al. 2012). We assume that Y_t is a random variable with mean ξ and standard deviation σ that follows a cumulative distribution function $Z(.)$. Then the number of vaccines obtained in period t, Q_t, satisfies $Q_t = Y_t n_t$, where n_t is the number of planned eggs in period t. Moreover, we set c as the unit cost of a planned egg and assume that it remains unchanged among the periods. Any unsold vaccines cannot be sold in the subsequent flu seasons and does have any salvage value because flu virus changes every year. The manufacturer is profit maximizing and know the demand relations among the periods, so they will predict the demands and decide the number of planned eggs in each period.

2.3.3 Epidemiology

In this study we use the susceptible, infected, and recovered (SIR) model to predict the disease spread (Hethcote 2000). We acknowledge that vaccines are not perfect, which means the vaccinated could still be infected. We use ϕ to denote vaccine effectiveness, which embrace the susceptibility and infectiousness effects (Longini Jr et al. 1996, Weycker et al. 2005, Chick et al. 2008). Let $H(f_t)$ and $P(f_t)$ be the infection probability functions for the vaccinated and non-vaccinated, respectively. Letting $r(f_t)$ be the infection probability for the whole population, we have $r(f_t) = f_t H(f_t) + (1 - f_t)P(f_t)$ (Bauch and Earn 2004, Adida et al. 2013). Obviously, all these infection probabilities decrease with f_t. Vaccination not only enhances the probability of the vaccinated to become immune to an infection, but also indirectly protects the non-vaccinated (Fine et al. 2011). Let R_0 be the basic reproduction number, which is a measure of the infectiousness of a disease (Anderson and May 1992, Murray 1993). When most of the population are immune, the chains of infection are likely to be disrupted, which stops the spread of the disease. When the coverage achieves a certain level, the infection probability of the whole population decreases to zero (Merrill 2015). This situation is called herd immunity. We denote f_{cf} as the minimum coverage to achieve herd immunity, which is known as the critical fraction. According to Diekmann and Heesterbeek (2000), $f_{cf} = \frac{R_0 - 1}{\phi R_0}$. If the vaccination coverage f_t is zero, $P(f_t) = r(f_t)$; if the vaccine coverage f_t achieves f_{cf}, $H(f_t) = P(f_t) = r(f_t) = 0$; otherwise, $P(f_t) > H(f_t)$.

Table 2.1 summarizes the major notation used in this paper.

2.4 Two-period Decisions

We model a two-period vaccine market consisting of individuals, a manufacturer and a government. Individuals make their own decisions based on the infection probability in the last flu season. We show the demand relations among the periods in Section 2.4.1. Knowing the among-period demand relations, the manufacturer decides the production quantity in each period to maximize its total profit over the two periods. We derive the profit-maximizing coverage in Section 2.4.2. In Section

Table 2.1: Notation

f_t	vaccination coverage in period t.
α	The proportion of myopic consumers in the population.
β	The proportion of free-riding consumers in the population.
Y_t	The average production per egg in period t.
$Z(.)$	Probability density function of Y_t.
n_t	The number of planned eggs in period t.
Q_t	The number of obtained vaccines in period t.
c	The unit cost of planned eggs.
ϕ	Vaccine effectiveness.
$H(f_t)$	Infection probability for vaccinated people according the vaccination coverage in period t.
$P(f_t)$	Infection probability for non-vaccinated people according the vaccination coverage in period t.
$r(f_t)$	Infection probability for the whole population according the vaccination coverage in period t.
N	The number of individuals in the population.
u	Individual's infection loss.
$g(.)$	Probability density function of u.
$G(.)$	Cumulative distribution function of u.
w	The vaccination cost per person.
d_t	Vaccine demand in period t.
π_{2P}	Manufacturer's profit for two periods.
π_{MP}	Manufacturer's profit for M periods.
TC_{1P}	The total social cost for one period.
TC_{2P}	The total social cost for two periods.
TC_{MP}	The total social cost for M periods.

2.4.3 we derive the two-period socially optimal coverage from the perspective of the government, where the government considers both individuals' utility and the manufacturer's profit.

2.4.1 Demand Relations

We consider a population consisting of N individuals. u is the infection loss of an individual. We assume that $u \in [0, 1]$ and every individual has an expectation of the infection cost (Meltzer et al. 1999, Galvani et al. 2007, Arifoğlu et al. 2012). Based on the demand model in Section 2.3.1, u is a random variable with probability density function $g(.)$ and cumulative probability distribution $G(.)$ for both strategic consumers and the whole population. Let w be the vaccination cost per person. To eliminate the case where no one is willing to receive vaccination, we assume w is smaller than 1. In addition, w and $g(u)$ do not vary among period.

As shown in Figure 2.1, the infection result of every individual can be one of the four categories: (i) vaccinated and infected, (ii) vaccinated and healthy, (iii) non-vaccinated and infected, and (iv) non-vaccinated and healthy, each with some probability. Vaccinated infected people has a cost of $w+u$ with probability $f_tH(f_t)$; vaccinated healthy people has a cost of w with probability $f_t[1-H(f_t)]$; non-vaccinated infected people has a cost of u with probability $(1-f_t)P(f_t)$; non-vaccinated healthy people has a cost of 0 with a probability of $(1-f_t)[1-P(f_t)]$. As a whole, expected cost for vaccinated people and non-vaccinated people is $w + uH(f_t)$ and $uP(f_t)$, respectively.

The vaccination coverage in period t, f_t, is restricted by the vaccine demand and supply in the period. So $f_t = min\{d_t, \frac{Q_t}{N}\}$, where d_t is the vaccine demand and $\frac{Q_t}{N}$ is the vaccine supply. When the supply is less than the demand in a certain period, every individual that would like to receive vaccination has the same probability to be vaccinated.

In the multi-period model, people make decisions at the beginning of each flu season. All people make decisions at the same time and have no idea about other people's choices. So they make decisions based on the infection probability in the last

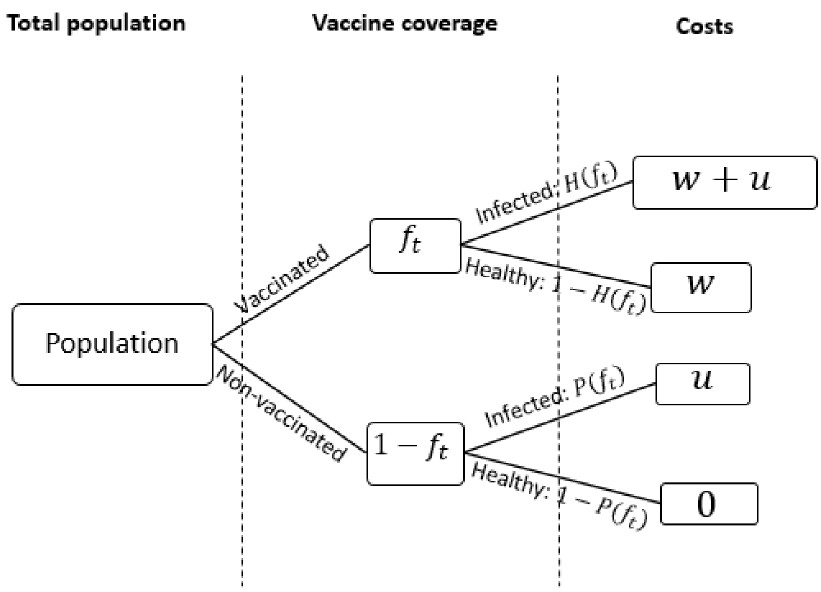

Figure 2.1: Consumer vaccination cost

flu season. For example, in period $t+1$, people consider that vaccinated people have a probability of $H(f_t)$ to be infected and non-vaccinated people have a probability of $P(f_t)$ to be infected. Strategic consumers compare their own vaccination cost with non-vaccination cost and make choices. The marginal individual that is a strategic consumer does not have any difference in receiving vaccination or not. u^m_{t+1} is the infection cost of the marginal individual in period $t+1$. Then we have

$$w + H(f_t)u^m_{t+1} = P(f_t)u^m_{t+1}. \tag{2.1}$$

People whose infection cost is higher than the infection cost of the marginal individual, i.e., $u > u^m_{t+1}$, receive vaccination and others do not receive vaccination. Then we get the demand in period $t+1$, i.e., $d_{t+1}(f_t) = \bar{G}(u^m_{t+1})$, where $\bar{G}(u^m_{t+1}) = 1 - G(u^m_{t+1})$. Demand relations between d_{t+1} and f_t are presented in Proposition 1.

Proposition 1. *The demand in period* $t+1$*,* d_{t+1}*, is a function of the coverage in period* t*,* f_t*, :*

$$d_{t+1}(f_t) = (1-\alpha-\beta)(1 - G(\frac{w}{P(f_t) - H(f_t)})) + \alpha$$

where $f_t = min\{d_t, \frac{Q_t}{N}\}$.

Proposition 1 indicates that the demand in period $t+1$ is related to the coverage in period t. Then f_{t+1} is influenced by both f_t and the production uncertainty in period $t+1$. The marginal individual in period $t+1$ is indifferent to receiving vaccination or not under the infection probability of period t. Obviously, $G(.)$ is an increasing function of u and w does not vary among the periods. Proposition 1 shows that the demand in period $t+1$ is strongly related to $P(f_t)-H(f_t)$, i.e., the infection probability gap between the vaccinated and the non-vaccinated. The marginal-benefit infection probability of a vaccination, $\frac{d(P(f_t)-H(f_t))}{df_t}$, means the change in infection probability benefit per vaccination. Besides, the demand decreases with w. A higher infection cost stimulates people to receive vaccination and a higher vaccination cost decreases people's willingness to receive vaccination.

We derive estimations of $r(f)$ and $H(f)$ from Mamani et al. (2012) as follows:

$$r(f) = \begin{cases} 0 & \text{if } f > \dfrac{R_0 - 1}{\phi R_0} \\ 1 - \phi f - \dfrac{1}{R_0} & \text{otherwise} \end{cases}$$

$$H(f) = \eta(1-\phi)r(f)$$

where ϕ is vaccine effectiveness, R_0 is the basic reproduction number (Anderson and May 1992) and η is a constant. Then we can get Proposition 2.

Proposition 2. *(1) If vaccine effectiveness ϕ satisfies $\phi > 1-\frac{1}{R_0}$, vaccine demand in period $t+1$ decreases with the coverage in period t.*

(2) If vaccine effectiveness ϕ satisfies $\phi < 1-\frac{1}{R_0}$, vaccine demand in period $t+1$ increases with the coverage in period t.

(3) If vaccine effectiveness ϕ satisfies $\phi = 1-\frac{1}{R_0}$, vaccine demand in period $t+1$ does not change with the coverage in period t.

Proposition 2 divides vaccines into three types by vaccine effectiveness. Figure 2.2 shows the relationships between d_{t+1} and f_t for different types of vaccines. Proposition 2 (1) illustrates the situation of $\phi > 1-\frac{1}{R_0}$, where the critical fraction is less than one. When the coverage achieves the critical fraction, the whole population is safe and $r(f_t) = 0$. The higher the coverage in period t is, the lower is the demand

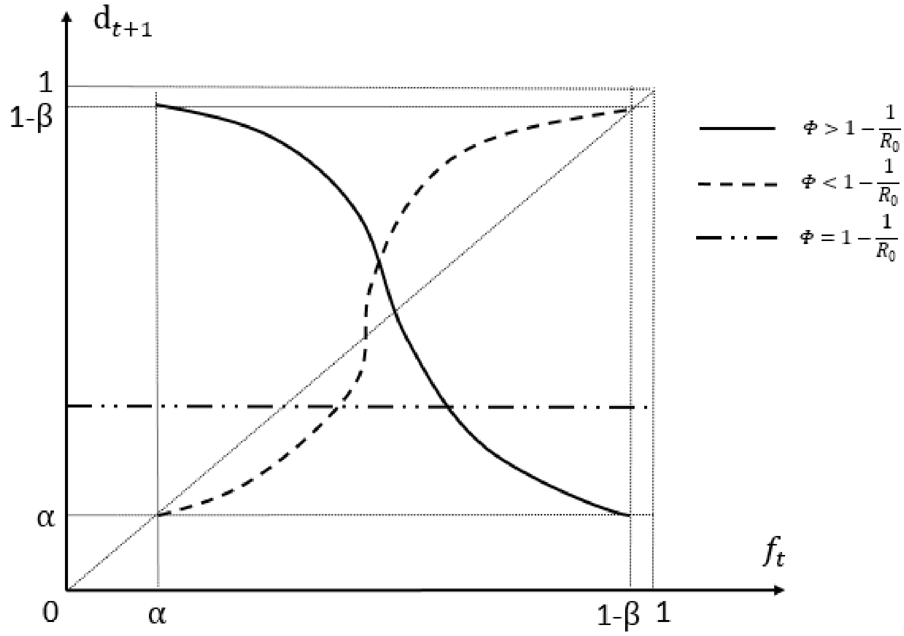

Figure 2.2: Demand relations and vaccine effectiveness

in period $t+1$. At this time, the marginal-benefit infection probability of vaccination, $\frac{d[P(f_t)-H(f_t)]}{df_t}$, is less than 0. The infection probability gap between vaccination and non-vaccination, $P(f_t) - H(f_t)$, decreases with f_t. So the willingness to receive vaccination decreases with f_t. A high coverage leads to extremely low demand in the next period. When the coverage is low, this kind of unwillingness is weakened and the high infection probability stimulates more people to receive vaccination in period $t+1$. Therefore, when vaccine effectiveness ϕ satisfies $\phi > 1 - \frac{1}{R_0}$, the vaccine demand in period $t+1$ decreases with the coverage in period t.

Proposition 2 (2) illustrates the situation of $\phi < 1 - \frac{1}{R_0}$, where the critical fraction is greater than one. In this situation, even though all the people are vaccinated, there are still people that might be infected. Vaccine demand increases with the coverage in the last period. At this time, the marginal-benefit infection probability of vaccination, $\frac{d[P(f_t)-H(f_t)]}{df_t}$, is larger than 0. The infection probability gap between vaccination and non-vaccination, $P(f_t) - H(f_t)$, increases with f_t. This means the marginal benefit of vaccination increases with f_t. So the willingness to receive vaccination increases with the coverage. A higher coverage in period t stimulates more vaccine demand in period $t+1$. Consumers are willing to receive vaccination to avoid incurring more infection expenses. Therefore, when vaccine effectiveness ϕ satisfies $\phi < 1 - \frac{1}{R_0}$, the vaccines demand in period $t+1$ increases with the coverage in period t.

Proposition 2 (3) shows that when vaccine effectiveness satisfies $\phi = 1 - \frac{1}{R_0}$, the vaccine demand in period $t+1$ does not change with the coverage in period t and the vaccine demand in period $t+1$ is a constant function of f_t. But in reality, virus changes every year. Vaccine effectiveness is out of the manufacture's control and it is hard to keep the effectiveness at a fixed level over several flu seasons. So this situation cannot last for several flu seasons, and we do not discuss this situation in detail in our study.

Lemma 1. *If the vaccine effectiveness always satisfies $\phi > 1 - \frac{1}{R_0}$, then $d_{t+1}(\alpha) = 1-\beta$ and $d_{t+1}(1-\beta) = \alpha$. Besides, the demand is always below the critical fraction, i.e. $1 - \beta = f_{cf}$.*

Lemma 1 implies that the coverage fluctuation will become smaller. When $\phi > 1 - \frac{1}{R_0}$, if $d_{t+1}(1-\beta) > \alpha$, then the coverage could not achieve $d^{-1}_{t+1}(\alpha)$, i.e., $f_t \leq 1 - \beta < d^{-1}_{t+1}(\alpha)$, where $d_{t+1}(f_t)$ is a strictly decreasing function. People between $d_{t+1}(1-\beta)$ and α would never be stimulated to receive vaccination. Therefore, in the multi-period situation, if vaccine effectiveness satisfies $\phi > 1 - \frac{1}{R_0}$, then $d_{t+1}(\alpha) = 1 - \beta$ and $d_{t+1}(1-\beta) = \alpha$. But, in reality, vaccine effectiveness is out of the manufacturer's control. So vaccine effectiveness may not always satisfy $\phi > 1 - \frac{1}{R_0}$. For simplicity, we set $d_{t+1}(\alpha) = 1 - \beta$ and $d_{t+1}(1-\beta) = \alpha$ for vaccines $\phi > 1 - \frac{1}{R_0}$ and $d_{t+1}(\alpha) = \alpha$ and $d_{t+1}(1-\beta) = 1 - \beta$ for vaccines $\phi < 1 - \frac{1}{R_0}$ in Figure 2.2. Besides, Lemma 1 also shows that the vaccine demand is always lower than f_{cf}. When $\phi > 1 - \frac{1}{R_0}$, $1 - \beta = f_{cf}$. When $\phi < 1 - \frac{1}{R_0}$, $f_{cf} \geq 1$. And β is hardly equal to 0. So the demand is always below f_{cf} in a free market without government interventions.

Lemma 2. *When $\phi > 1 - \frac{1}{R_0}$, there must exist f_0 satisfying $d_{t+1}(f_0) = f_0$. For all $f_t > f_0$, $d_{t+1}(f_t) \leq f_0$; for all $f_t < f_0$, $d_{t+1}(f_t) \geq f_0$.*

Lemma 2 shows that, in the situation of Proposition 2 (1), if the coverage converges to a certain value, it will be f_0. The coverage convergence also depends on the distribution function $G(.)$. Proposition 7 later characterizes the related coverage convergence.

2.4.2 Profit-maximizing Coverage

Research on the vaccine supply chain has studied the efficiency of vaccine production, most of which concerns the single-period setting. In reality, the manufacturer may formulate a multi-period plan to improve its total profit. In the two-period model, the manufacturer decides the number of planned eggs in each period that maximizes its expected profit over the two periods π_{2P} as follows:

$$max\ \pi_{2P}(n_t, n_{t+1}) = wNE[f_t] - cn_t + wNE[f_{t+1}] - cn_{t+1}$$

where $f_i = min\{d_i, \frac{Q_i}{N}\} = min\{d_i, \frac{n_i Y_i}{N}\}$ for $i = t, t+1$.

Proposition 3. *The profit-maximizing numbers of planned eggs, n_t^* and n_{t+1}^*, in a two-period problem are consistent with that in a single period problem and satisfy*

$$w\int_0^j y dZ_y(y) = c$$

where $j = \frac{Nd_t}{n_t^*}$ for period t and $j = \frac{Nd_{t+1}}{n_{t+1}^*}$ for period t+1.

Proposition 3 is similar to the Proposition 4 in Arifoğlu et al. (2012), who derive the profit-maximizing production quantity in the single-period model. This implies that in both single-period and multi-period models, the profit-maximizing production tries to meet the demand fully. We already assume that w, c and $g(.)$ do not change among the periods. From Proposition 3, we have $\frac{Nd_t}{n_t^*} = \frac{Nd_{t+1}}{n_{t+1}^*}$ for each period. The expected demand in a single-period model just repeats among periods. In the multi-period model, d_{t+1} changes with d_t, so the profit-maximizing coverage is different. Setting $\frac{Nd_t}{n_t^*} = \frac{Nd_{t+1}}{n_{t+1}^*} = K_0$, we have $d_t = \frac{K_0 n_t^*}{N}$ and $d_{t+1} = \frac{K_0 n_{t+1}^*}{N}$. Then $f_t = min\{\frac{K_0 n_t^*}{N}, \frac{Y_t n_t^*}{N}\}$, where the first term denotes the expected production (= expected demand) and the second term denotes the actual production. We set $h_t = min\{K_0, Y_t\}$, then $f_t = \frac{n_t^* h_t}{N}$ and $f_{t+1} = \frac{n_{t+1}^* h_{t+1}}{N}$. For the single-period problem, the manufacturer seeks to satisfy the demand in one period and makes the biggest profit for this period. For the two-period problem where a high coverage in one period might lead to extremely low demand in the next period, so fully meeting the demand in a period might not be optimal for the manufacturer. From Proposition 1, we see that the maximizing profit is a function of f_t. Then we can find f_{t+1} by Proposition 1, n_t and n_{t+1} by $f_t = \frac{n_t^* h_t}{N}$ and $f_{t+1} = \frac{n_{t+1}^* h_{t+1}}{N}$, respectively. So

$$\pi_{2P}(f_t) = (w - \frac{c}{h_t})Nf_t + (w - \frac{c}{h_{t+1}})Nf_{t+1} = e_t f_t + e_{t+1} f_{t+1}, \tag{2.2}$$

where $e_t = (w - \frac{c}{h_t})N$ and $e_{t+1} = (w - \frac{c}{h_{t+1}})N$. $B(f_t) = \frac{\pi(f_t)}{e_{t+1}} = k_t f_t + f_{t+1}$. We ignore the case $h_t \geq \frac{c}{w}$, where the manufacturer cannot make any profit from vaccine production. f_{2P}^{M*} is the profit-maximizing coverage in period t for two-period production.

Proposition 4. *(1) When $\phi > 1 - \frac{1}{R_0}$, f_{2P}^{M*} satisfies $\frac{dB}{df_t} = 0$. And f_{2P}^{M*} increases with k_t.*

(2) When $\phi < 1 - \frac{1}{R_0}$, f_{2P}^{M*} is $1 - \beta$. And the situation does not change with the actual production.

Proposition 4 (1) illustrates the situation of $\phi > 1 - \frac{1}{R_0}$. The manufacturer gets the maximum profit when the expected coverage satisfies $\frac{dB}{df_t} = 0$. The sufficient condition of $\frac{d^2B}{df_t^2} \leq 0$ is $\frac{2\phi g(j)}{1 - \phi f_t - \frac{1}{r_0}} + g^{'}(j) \geq 0$. This assumption holds in some common distribution cases including normal distribution and uniform distribution. Under this situation, f_{2P}^{M*} increases with k_t. It means f_{2P}^{M*} increases with the actual production in period t and decreases with the actual production in period $t+1$. When the production in period t is as expected (i.e., $Y_t = K_0$), if $Y_{t+1} < K_0$, the production shortage in period $t+1$ leads to un-met demand and a sub-optimal situation. When the production in period $t+1$ is as expected (i.e., $Y_{t+1} = K_0$), if $Y_t < K_0$, the production shortage in period t leads to un-met demand in period t and a lower demand in period $t+1$. If $Y_t < K_0$, $Y_{t+1} < K_0$ and $k_t = 1$, f_{2P}^{M*} is the same as the value when $Y_t = Y_{t+1} = K_0$. But the total profit decreases, because $\pi(f_t) = e_{t+1}B(f_t)$ decreases with e_{t+1}. All these inefficiencies result from production uncertainty.

Proposition 4 (2) implies that, when $\phi < 1 - \frac{1}{R_0}$, regardless of whether or not the actual production in periods t and $t+1$ is equal to the expected production, the profit-maximizing coverage is the highest coverage. This result is consistent with Proposition 2 (2). The demand in the period $t+1$ increases with the coverage in period t. No matter what the actual production is, the total two-period profit increases with the coverage. The optimal solution is to make the coverage achieve the highest level.

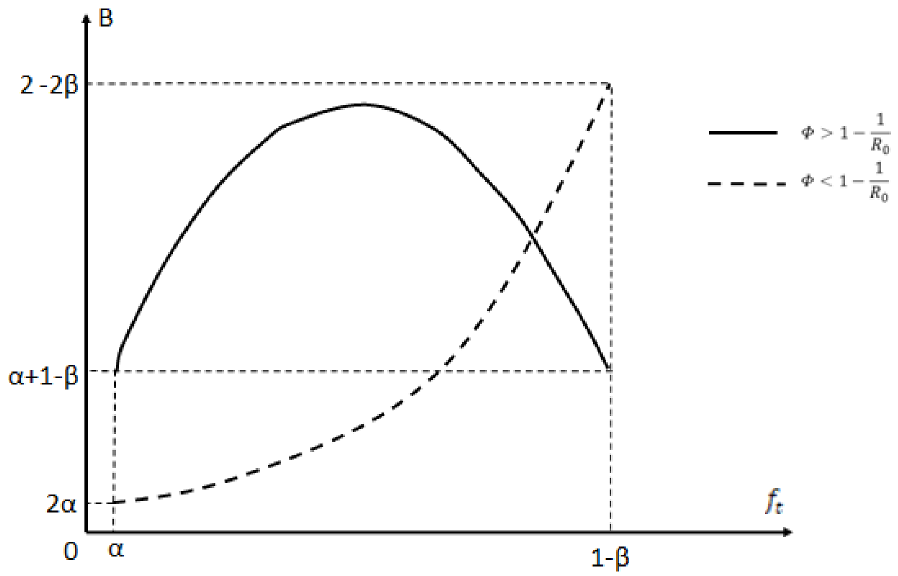

Figure 2.3: Manufacturer's profit and vaccination coverage

Referring to the assumption for Figure 2.2, Figure 2.3 shows the situation of $k_t = 1$, where $B(\alpha) = B(1-\beta)$ for $\phi > 1 - \frac{1}{R_0}$. The actual production in periods t and $t+1$ is not less than the expected production when $k_t = 1$. When $k_t < 1$, the actual production in period $t+1$ is equal to the expected production and the actual production in period t is less than the expected production. At this time, $B(\alpha) > B(1-\beta)$. Demand in period t decreases. It makes unmet demand smaller and makes lost profit lower. When $k_t > 1$, the actual production in period t is equal to the expected production and the actual production in period $t+1$ is less than the expected production. In this situation, $B(\alpha) < B(1-\beta)$. Demand in period t increases and demand in period $t+1$ decreases. This makes a higher profit in period t and leads to a smaller unmet demand in period t.

Sometimes different types of vaccines have different infection probabilities, and different prices and costs, e.g., the trivalent influenza vaccine and the tetravalent influenza vaccine sell at different prices. When deciding the vaccine product type, the manufacturer expects the actual production to be the expected production, i.e., $Y_t = Y_{t+1} = K_0$. Then, $d_t = f_t$. Let f_I be the unique solution of $\pi_a(f_t) = \pi_b(f_t)$.

Proposition 5. *(1) If $(w_a - \frac{c_a}{K_0})(1 + \alpha - \beta) \geq 2(w_b - \frac{c_b}{K_0})(1 - \beta)$, vaccines that $\phi > 1 - \frac{1}{R_0}$ are always better.*

(2) If $(w_a - \frac{c_a}{K_0})(1 + \alpha - \beta) < 2(w_b - \frac{c_b}{K_0})(1 - \beta)$, the situation varies with the vaccine prices and costs. When $\alpha < d_t \leq f_I$, producing vaccines that $\phi > 1 - \frac{1}{R_0}$ can make more profit. When $f_I < d_t < 1 - \beta$, vaccines that $\phi < 1 - \frac{1}{R_0}$ can make more profit.

Proposition 5 implies that, for different expected demands in period t, choosing the right vaccine type could improve the manufacturer's profit. The choice depends on vaccine price, vaccine costs, e_t, and e_{t+1}. Figure 4 shows the situations of $e_t = e_{t+1}$ and $w_a - \frac{c_a}{K_0} = w_b - \frac{c_b}{K_0}$. Proposition 3 suggests that the optimal number of planned eggs is determined by fully meeting the demand d_t. In the multi-period model, the demand in each period is related to the situation in the last period. The relationship between d_{t+1} and f_t is strongly influenced by vaccine effectiveness. For different vaccine types with different vaccine effectiveness, the expected changes in coverage vary widely. So a right choice of vaccine enables the manufacturer to make more profit, as sated in Proposition 5.

2.4.3 Socially Optimal Coverage

The government considers not only people's utility but also the manufacturer's profit. The government cooperates with the manufacturer and controls the production quantity to maximize the total social utility. The government could make direct purchase or require compulsory vaccination to stimulate consumers to receive vaccination (Arifoğlu et al. 2012), so the socially optimal coverage is in the interval [0,1] rather than $[\alpha, 1-\beta]$. We assume that the government considers the population as the priority group. The total social utility consists of the manufacturer's profit and m times the utility of the whole population, where m is not less than one.

First, we consider the single-period situation. The utility per individual is given by

$$PU = \bar{V} - wf_t - H(f_t)\int_{u_t}^{1} vdG(v) - P(f_t)\int_{0}^{u_t} vdG(v)$$

where $\bar{V}$ is the utility of a healthy person. The second term is the expected cost of taking vaccine; the third term and the fourth term are the expected infection cost for vaccinated people and non-vaccinated people, respectively.

The manufacturer's profit is

$$MP = wNf_t - \frac{cNf_t}{K_0}$$

where the first term is the revenue of selling vaccines and the second term is the cost of production.

The government wants to maximize the total social utility, i.e.,

$$max\{m \times PU + \frac{MP}{N}\}$$

by achieving the socially optimal coverage for the single-period problem, i.e., f_{1P}^{G*}.

TC_{1P} is the total social cost in period t and f_{1P}^{G*} is the socially optimal coverage for the single-period model.

$$min\{TC_{1P}(f_t)\} = mH(f_t)\int_{u_t}^{1} vdG(v) + mP(f_t)\int_{0}^{u_t} vdG(v) + (m-1)wf_t + \frac{cf_t}{K_0}$$

where $u_t = \bar{G}^{-1}(f_t)$.

Solving it, we derive f_{1P}^{G*} in Lemma 3. Let f_{II} be the unique solution of $\frac{dTC_{1P}}{df_t} = 0$.

Lemma 3. *(1) If* $\phi > 1 - \frac{1}{R_0}$*,*

$$f_{1P}^{G*} = \begin{cases} 0 & \text{if } f_{II} < 0, \\ 1 & \text{if } f_{II} > 1, \\ f_{II} & \text{otherwise} \end{cases}$$

(2) When $\phi < 1 - \frac{1}{R_0}$*,*

$$f_{1P}^{G*} = \begin{cases} 0 & \text{if } \tau < 0, \\ 1 & \text{otherwise} \end{cases}$$

where $\tau = mL(P(0) - H(1)) - (m-1)W - C/K_0$.

Lemma 3 gives the socially optimal coverages for different vaccine effectiveness in the single-period model. While the optimal situation has been studied in the literature, few studies consider the situation where $\phi < 1 - \frac{1}{R_0}$ and three types of consumers. In the two-period situation, the total social cost consists of the social cost in period t and the social cost in period $t+1$. The socially optimal coverage achieves the minimum social cost in two periods. TC_{2P} is the total cost for the two periods. So the government's problem is given by

$$min\{TC_{2P}(f_t)\} = TC_{1P}(f_t) + TC_{1P}(f_{t+1})$$

where f_{2P}^{G*} is the socially optimal coverage in period t for the two-period problem. We characterize the relationship between f_{2P}^{G*} and f_{1P}^{G*} in Proposition 6.

Proposition 6. *(1) If $\phi > 1 - \frac{1}{R_0}$, f_{2P}^{G*} and f_{1P}^{G*} are in the same side of f_0. And f_{2P}^{G*} will be closer to f_0 than f_{1P}^{G*}.*

$$\begin{cases} f_{2P}^{G*} > f_{1P}^{G*} & \textit{if } f_{II} < f_0, \\ f_{2P}^{G*} \leq f_{1P}^{G*} & \textit{if } f_{II} \geq f_0, \end{cases}$$

where f_{II} satisfies $\frac{dTC_{1P}}{df_t} = 0$.

(2) If $\phi < 1 - \frac{1}{R_0}$,

$$\begin{cases} f_{2P}^{G*} \geq 0 & \textit{if } \tau < 0, \\ f_{2P}^{G*} \leq 1 & \textit{otherwise} \end{cases}$$

where $\tau = mL(P(0) - H(1)) - (m-1)W - C/K_0$.

Proposition 6 (1) shows the situation of $\phi > 1 - \frac{1}{R_0}$. It is strongly related to Proposition 2 (1) which shows f_{t+1} is a decreasing function of f_t. Set $f_V = d_{t+1}^{-1}(f_{II})$. If there are some f_t in the interval $[0, 1]$ satisfing $min\{f_{II}, f_V\} \leq f_t \leq max\{f_{II}, f_V\}$, f_{2P}^{G*} will be one of them. That $f_t = f_{II}$ means achieving the minimum social cost in period t and that $f_t = f_V$ means achieving the minimum social cost in period $t+1$. In two-period problem, the government considers the social cost in two periods at the same time. So f_{2P}^{G*} is a compromise between f_{II} and f_V. Then we consider different situations respectively. When $max\{f_{II}, f_V\} \leq 0$, $f_{2P}^{G*} = f_{1P}^{G*} = 0$. It means that both of the social costs in periods t and $t+1$ achieve the minimum value when

$f_t = 0$. So $f_{2P}^{G*} = 0$. When $min\{f_{II}, f_V\} \leq 0 < max\{f_{II}, f_V\}$, $f_{2P}^{G*} \geq f_{1P}^{G*} = 0$. Either f_{II} or f_V is higher than 0 and the other is 0. f_{2P}^{G*} will be in $[0, max\{f_{II}, f_V\}]$. The situation of $min\{f_{II}, f_V\} \geq 1$ is similar to the situation of $max\{f_{II}, f_V\} \leq 0$. Both the socially optimal coverage in periods t and $t+1$ achieve the minimum value when $f_t = 1$. So the optimal situation of the two-period problem is $f_t = f_{t+1} = 1$. When $min\{f_{II}, f_V\} < 1 \leq max\{f_{II}, f_V\}$, $f_{2P}^* \leq f_{1P}^* = 1$. Either f_{II} or f_V is lower than 1 and the other is 1. So f_{2P}^{G*} will be in $[min\{f_{II}, f_V\}, 1]$. The last condition is $min\{f_{II}, f_V\} > 0$ and $max\{f_{II}, f_V\} < 1$. In $[0, min\{f_{II}, f_V\}]$, $TC_{2P}(f_t)$ is a decreasing function of f_t. In $[max\{f_{II}, f_V\}, 1]$, $TC_{2P}(f_t)$ is an increasing function of f_t. So f_{2P}^{G*} will be in the interval $[min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$. We have already known that either f_{II} or f_V is higher than f_0 and the other is lower than f_0. As a whole, when $f_{II} < f_0$, $f_{2P}^{G*} > f_{1P}^{G*}$; when $f_{II} \geq f_0$, $f_{2P}^{G*} \leq f_{1P}^{G*}$. Both f_{2P}^{G*} and f_{1P}^{G*} are on the same side of f_0. And f_{2P}^{G*} will be closer to f_0 than f_{1P}^{G*}.

Proposition 6 (2) implies the situation of $\phi < 1 - \frac{1}{R_0}$. Proposition 2 (2) shows that f_{t+1} is an increasing function of f_t. When $f_t \leq min\{f_{II}, f_V\}$, TC_{2P} is an increasing function of f_t. When $f_t > max\{f_{II}, f_V\}$, TC_{2P} is a decreasing function of f_t. So if $max\{f_{II}, f_V\} < 0$, $f_{2P}^{G*} = f_{1P}^{G*} = 1$. If $min\{f_{II}, f_V\} > 1$, $f_{2P}^{G*} = f_{1P}^{G*} = 0$. Otherwise, f_{2P}^{G*} is 0, 1, or in the interval $[min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$. We need to compare the social cost of $f_t = 0$, $f_t = 1$ and $f_t \in [min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$ to get the socially optimal coverage.

2.5 Multi-period Plan

In this section we extend the two-period model to a multi-period model. We study the coverage convergence in Section 2.5.1. Then we consider an M-period model to characterize the profit-maximizing coverage in Section 2.5.2 and the socially optimal coverage in Section 2.5.3.

2.5.1 Coverage Convergence

We have already found the demand relations among periods. Regarding Proposition 2 and Lemma 1, the whole population is hardly in a safe status in a free market without government intervention, although the supply is sufficient. Then we explore the characteristics about the convergence of the coverage. In a free market with sufficient supply and without government intervention, the coverage in every period is equal to the vaccine demand. Following the demand relations, we characterize coverage convergence in Proposition 7. f_0 is the convergence value from Lemma 2. And we set $J_i(f_i) = (1-\alpha-\beta)(1-G(\frac{w(1-f_i)}{r(f_i)-H(f_i)})) + \alpha$ for $i = t, t+1$ for expression simplicity.

Proposition 7. *(1) For vaccines that $\phi > 1 - \frac{1}{R_0}$, in a free market with sufficient vaccine supply and without government intervention, the coverage convergence is as below:*

a. If $J_{t+1}(J_t(f_t)) < f_t$ for $f_t > f_0$ or $J_{t+1}(J_t(f_t)) > f_t$ for $f_t < f_0$, the coverage converges to f_0;

b. If $J_{t+1}(J_t(f_t)) > f_t$ for $f_t > f_0$ or $J_{t+1}(J_t(f_t)) < f_t$ for $f_t < f_0$, the coverage does not converge to a certain value and coverage fluctuation will become larger and larger;

c. If $J_{t+1}(J_t(f_t)) = f_t$, the coverage follows an alternating sequence and the fluctuation keeps the same;

(2) For vaccines that $\phi < 1 - \frac{1}{R_0}$, in a free market with sufficient vaccine supply and without government intervention, the coverage convergence is as below:

d. If $J_t(f_t) < f_t$ for all f_t, the coverage converges to the minimum coverage α;

e. If $J_t(f_t) > f_t$ for all f_t, the coverage converges to the maximum coverage $1-\beta$;

f. If $J_t(f_t) = f_t$ for all f_t, the coverage keeps the same;

Figure 2.4 shows the six situations of coverage convergence in Proposition 7. We find that the coverage convergence is strongly related to the distribution of $g(.)$, because $g(.)$ decides $d_{t+1}(f_t)$. Proposition 7 (1) shows the situation of $\phi > 1 - \frac{1}{R_0}$. For case (1)a, the coverage fluctuation gradually decreases and then the coverage converges to f_0. We get f_0 from Lemma 2 and the value of f_0 depends on α, β and $g(.)$. Based on some real-life reported data and related studies, stable coverage achieved in a free market is always below the socially optimal level (Philipson 2000). But it reminds the government that, if the converge value in a certain city is close

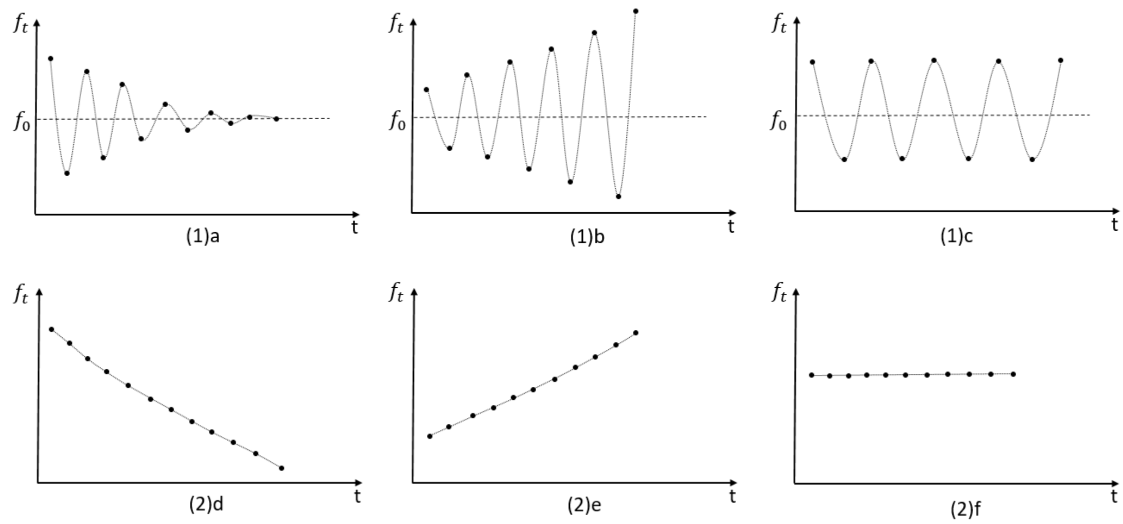

Figure 2.4: Six types of coverage convergence

to the target coverage, once the coverage achieves the socially optimal level under government intervention, the coverage could maintain in the optimal level. For case (1)b, the coverage follows an alternating sequence and the fluctuation increases. The coverage tends to an unstable status. It is easy to lead to an extremely low coverage and a disease outbreak. For case (1)c, the coverage follows an alternating sequence and the fluctuation keeps the same. Because of the uncertainty of the vaccine effectiveness and $g(.)$, this situation would not last for a long time.

Proposition 7 (2) implies the situation of $\phi < 1 - \frac{1}{R_0}$. For case (2)d, the coverage gradually converges to the minimum coverage. A low coverage is easy to lead to a disease outbreak and make the whole population in a dangerous status. For case (2)e, the coverage converges to the maximum coverage. In this situation, once the supply is sufficient, the coverage will tend to a safe coverage. For case (2)f, the coverage keeps the same. Because of the uncertainty of the vaccine effectiveness and $g(.)$, this situation would not last for a long time.

2.5.2 Multi-period Production

We consider an M-period model, where $M > 2$. Restricted by our results from the two-period model, we assume M is even. In the multi-period situation, the manufacturer decides the number of planed eggs for every periods and wants to maximize the total expected profit. π_{MP} is the profit for multi-period production. Thus, the production problem is

$$max\ \pi_{MP}(n_t, n_{t+1}, ..., n_M) = wNE[f_t]-cn_t+wNE[f_{t+1}]-cn_{t+1}+...+wNE[f_M]-cn_M$$

where $f_t = min\{d_t, \frac{Q_t}{N}\} = min\{d_t, \frac{n_t Y_t}{N}\}$ for every period.

It's easy to prove that the result in Proposition 3 is also applicable in a multi-period model. The profit-maximizing number of planed eggs satisfies

$$w\int_0^j ydZ_y(y) = c$$

where $j = \frac{Nd_t}{n_t^*}$ for every period.

In a multi-period production plan, the manufacturer decides the production quantity in period t to maximize the total profit from period t to period M. We do not consider the production uncertainty in this section. It means $h_t = K_0 = Y_t$ for every period. Then the total expected profit, π_{MP}, is a function of f_t. The coverage in every period can be calculated by Proposition 1 and the correlated n_t in every period can be calculated by $f_t = \frac{n_t^* h_t}{N}$. f_{MP}^{M*} is the profit-maximizing coverage in period t in a multi-period situation and is given by

$$max\ \pi_{MP}(f_t) = (w - \frac{c}{h_t})Nf_t + (w - \frac{c}{h_{t+1}})Nf_{t+1} + ... + (w - \frac{c}{h_M})Nf_M$$

Regarding Equation (2.2), we have

$$max\ B_{MP}(f_t) = f_t + f_{t+1} + ... + f_M$$

Then we characterize f_{MP}^{M*} in Proposition 8.

Proposition 8. *(1) When $\phi > 1 - \frac{1}{R_0}$, f_{MP}^{M*} and f_{VI} are in the side of f_0.*

a. If $J_{t+1}(J_t(f_t)) < f_t$ for $f_t > f_0$ or $J_{t+1}(J_t(f_t)) > f_t$ for $f_t < f_0$, f_{VI} is closer than f_{MP}^{M*} to f_0.

$$\begin{cases} f_{MP}^{M*} < f_{VI} & \text{if } f_{VI} < f_0, \\ f_{MP}^{M*} \geq f_{VI} & \text{if } f_{VI} \geq f_0, \end{cases}$$

b. If $J_{t+1}(J_t(f_t)) > f_t$ for $f_t > f_0$ or $J_{t+1}(J_t(f_t)) < f_t$ for $f_t < f_0$, f_{MP}^{M*} is closer than f_{VI} to f_0.

$$\begin{cases} f_{MP}^{M*} > f_{VI} & \text{if } f_{VI} < f_0, \\ f_{MP}^{M*} \geq f_{VI} & \text{if } f_{VI} \geq f_0, \end{cases}$$

where f_{VI} is f_{2P}^{M*} when $h_t = h_{t+1}$.

(2) When $\phi < 1 - \frac{1}{R_0}$, the profit-maximizing coverage $f_{MP}^{M*} = f_{2P}^{M*} = 1 - \beta$. And the situation does not change with the actual production.

Proposition 8 characterizes some relations between f_{MP}^{M*} and f_{VI}. Proposition 8 (1) lists the situation of $\phi > 1 - \frac{1}{R_0}$. For case (1)a, the coverage will gradually be close to f_0. Once M is large enough, π_{MP} will be close to Mf_0. There is no the optimal coverage for M periods. If M is not large enough, we consider two situations. If $f_0 > f_{VI}$, we have $\frac{d\pi_{MP}}{df_t} \leq 0$ for all $f_t \geq f_{VI}$. Then f_{MP}^{M*} will be less than f_{VI}. If $f_0 \leq f_{VI}$, we have $\frac{d\pi_{MP}}{df_t} \geq 0$ for all $f_t \leq f_{VI}$. Then f_{MP}^{M*} will be higher than f_{VI}. So f_{MP}^{M*} and f_{VI} are on the same side of f_0, and f_{VI} is closer to f_0 than f_{MP}^{M*}. That $f_t = f_{VI}$ means making the highest profit in the first period. Because the manufacturer makes more profit when $f_t < f_{VI} < f_0$ than $f_{VI} < f_t < f_0$, and makes more profit when $f_t > f_{VI} > f_0$ than that when $f_{VI} > f_t > f_0$. When the coverage converges to f_0, the manufacturer cannot get optimal profit. So f_{MP}^{M*} is more away from f_0 than f_{VI}. On the other side, for case (1)b, the coverage will gradually be away from f_0. Then we have $\frac{d\pi_{MP}}{df_t} \leq 0$ for all $f_t \geq max\{f_0, f_{VI}\}$ and $\frac{d\pi_{MP}}{df_t} \geq 0$ for all $f_t \leq min\{f_0, f_{VI}\}$. And f_{MP}^{M*} will be in the interval $[min\{f_0, f_{VI}\}, max\{f_0, f_{VI}\}]$. As f_t increases from f_0, coverage fluctuation becomes larger and the profit decreases. The manufacturer cannot get optimal profit when the coverage fluctuation is large. So f_{MP}^{M*} is closer to f_0 than f_{VI}. Proposition 8 (2) shows the situation of $\phi < 1 - \frac{1}{R_0}$. We have $\frac{dB}{df_t} > 0$ and $\frac{df_{t+1}}{f_t} \leq 0$ for all f_t. So $\frac{d\pi_{MP}}{df_t} \geq 0$. The profit-maximizing coverage f_{MP}^{M*} is the same as f_{2P}^{M*}. And the situation does not change with the actual production. Referring to Proposition 2(2), people's willingness of taking vaccines increases with the coverage in the last period. Manufacturer's profit increases with the coverage.

2.5.3 Government Multi-period Plan

In this section we consider that government makes an M-period plan, where $M > 2$. TC_{MP} is the total social cost from period t to period M. The government seeks to minimize TC_{MP}, i.e.,

$$min\{TC_{MP}(f_t)\} = TC_{1P}(f_t) + TC_{1P}(f_{t+1}) + ... + TC_{1P}(f_{M-1}) + TC_{1P}(f_M) \quad (2.3)$$

The multi-period socially optimal coverage is f_{MP}^{G*}, which We characterize in the situation of $\phi > 1 - \frac{1}{R_0}$.

Proposition 9. *When $\phi > 1 - \frac{1}{R_0}$,*

a. If $J_{t+1}(J_t(f_t)) < f_t$ for $f_t > f_0$ or $J_{t+1}(J_t(f_t)) > f_t$ for $f_t < f_0$, f_{MP}^{G*} and f_{2P}^{G*} are in the same side of f_0,

$$\begin{cases} f_{MP}^{G*} < f_0 & \text{if } max\{f_{II}, f_V\} < f_0, \\ f_{MP}^{G*} \geq f_0 & \text{if } min\{f_{II}, f_V\} \geq f_0, \end{cases}$$

b. If $J_{t+1}(J_t(f_t)) > f_t$ for $f_t > f_0$ or $J_{t+1}(J_t(f_t)) < f_t$ for $f_t < f_0$, f_{MP}^{G*} is in the interval $[min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$, where f_{II} satisfies $\frac{dTC_{1P}}{df_{II}} = 0$, $f_V = d_{t+1}^{-1}(f_{II})$ and f_0 is the convergence value from Lemma 2.

Proposition 9 provides the results in the situation of f_{MP}^{G*} when $\phi > 1 - \frac{1}{R_0}$. In case a, f_{MP}^{G*} and f_{2P}^{G*} are on the same side of f_0. In case b, both f_{MP}^{G*} and f_{2P}^{G*} are in the interval $[min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$. This is consistent with Proposition 8 (1). The profit-maximizing coverage and socially optimal coverage are on the same side of f_0. This implies that the government should cooperate with the manufacturer to formulate a multi-period production plan, which helps make the government interventions more efficient.

2.5.4 Robustness Test

In this section we test the relationship between coverage and number of periods, and investigate the robustness of the basic reproduction number R_0. We assume that $c = 0.03$ and $w = 0.15$ (Galvani et al. 2007, Deo and Corbett 2009, CDC 2009). To simplify the calculation, Mamani et al. (2012) and Adida et al. (2013) assume that the infection cost follows a uniform distribution. Similarly, we assume that $g(.)$ follows a uniform distribution with mean 0.5 and standard deviation 1. Following Arifoğlu et al. (2012), we assume $\xi = 1$ and $\sigma = 0$, which means $Q_t = n_t$.

First, we test the multi-period profit-maximizing coverage and multi-period socially optimal coverage in comparison with demand convergence. Second, we investigate the robustness of the profit-maximizing coverage and socially optimal coverage with respect to the basic reproduction number R_0.

Effect of Number of Periods

In this section we take influenza vaccine for example. Then $R_0 = 3$ (Wikipedia 2018). We provide several types of demand convergence in Proposition 7. The demand varies among periods following Proposition 1. Propositions 8 (1) and 9 illustrate the multi-period profit-maximizing and multi-period socially optimal coverage for vaccine $\phi > 1 - \frac{1}{R_0}$. So we set $\phi = 0.8$, which satisfies $\phi > 1 - \frac{1}{R_0}$, in this section. Figure 2.5 (a) shows the demand varies among periods with $f_1 = 0.7$. When $g(.)$ follows $U(0,1)$, the coverage gradually converges to f_0. Following Proposition 7, we have $1 - G(J(1 - G(f_t))) < f_t$ for $f_t > f_0$ and $1 - G(J(1 - G(f_t))) > f_t$ for $f_t < f_0$. Figure 2.5 (b) shows the multi-period profit-maximizing and multi-period socially optimal coverage. When $g(.)$ follows $U(0,1)$, the profit-maximizing and socially optimal coverage for the same number of periods are the same. Following Proposition 8 (1) a, f_{MP}^{M*} and f_{2p}^{M*} are on the same side of f_0, and f_{MP}^{M*} is more away from f_0. Following Proposition 9 a, f_{MP}^{G*} and f_{2p}^{G*} are on the same side of f_0. This case shows that, when the number of periods is the same, the government and the manufacturer are highly consistent in their goals.

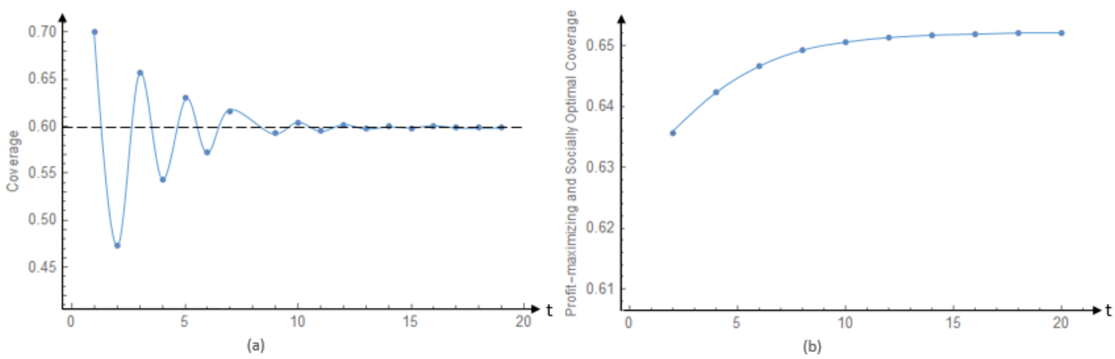

Figure 2.5: Sensitivity analysis on the number of periods

Robustness of the Basic Reproduction Number

R_0 represents the basic reproduction number, and is a measure of the infectiousness of a disease (Anderson and May 1992). For example, R_0 is in $[0.3, 0.8]$ for MERS, in $[2, 3]$ for influenza and in $[4, 7]$ for Mumps (Wikipedia 2018). So we study the two-period profit-maximizing coverage and the socially optimal coverage, and analyze their dependence in the basic reproduction number R_0. van Boven et al. (2013) get the proportion of myopic and free-riding consumers for Mumps vaccine as 0.12 and 0.17, respectively. We set $\alpha = 0.12$ and $\beta = 0.17$ in this section. We get the profit-maximizing coverage from Proposition 4 and the socially optimal coverage from Lemma 3. We let f^{M*} and f^{G*} denote them respectively. We ignore the priority that the government gives to the population, which means $m = 1$. We set $R_0 = 3$. The convergence value f_0 will be 0.5. Regarding vaccine effectiveness, we include two cases: $\phi > 1 - \frac{1}{R_0}$ and $\phi < 1 - \frac{1}{R_0}$. We set $\phi = 0.8$ in Figure 2.6 (a) and $\phi = 0.4$ in Figure 2.6 (b).

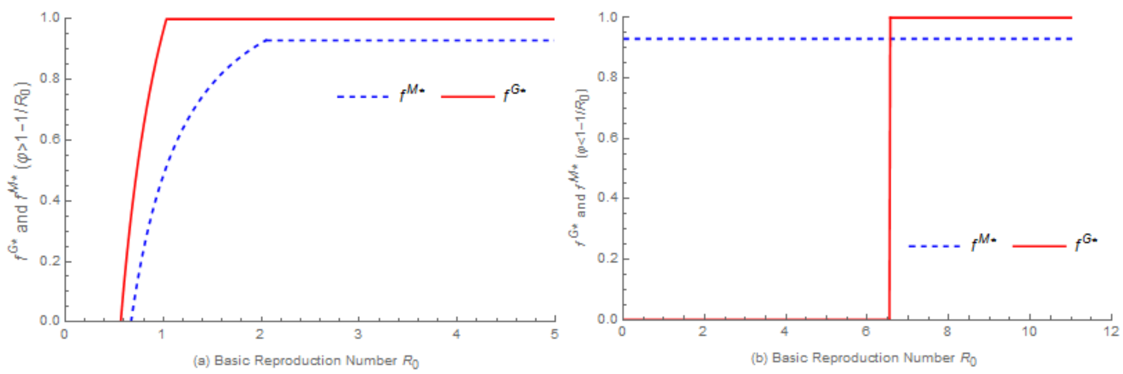

Figure 2.6: Sensitivity analysis on the basic reproduction number

Figure 2.6 (a) illustrates how f^{M*} and f^{G*} vary in R_0 when $\phi > 1 - \frac{1}{R_0}$. Both f^{G*} and f^{M*} increase with R_0. A disease with a higher R_0 is more infectious. So individuals will improve the coverage to avoid infections. As the demand increases, f^{M*} increases. And f^{G*} also increases. But f^{G*} is always larger than f^{M*}. Referring to Proposition 6 (1), f_{2P}^{G*} will be closer to f_0 than f_{1P}^{G*}. So when $f < f_0$, f_{2P}^{G*} is always higher than f_{2P}^{M*}. Under this situation, the government should intervene the supply side to improve the production quantity and sometimes intervene in the demand side. When $f > f_0$, f_{2P}^{G*} might be equal to f_{2P}^{M*}. The government just needs stimulate consumers to keep the demand at this value. Once f^{M*} achieves $1-\beta$, the coverage is restricted by free-riding consumers. At this time, the government can make direct purchase or require compulsory vaccination to improve vaccination coverage. Figure 2.6 (b) shows the situation of $\phi < 1-\frac{1}{R_0}$. When R_0 is low, $f^{G*}=0$. Because diseases are not seriously infectious and vaccines are not effective enough. So the government does not encourage consumers to receive vaccination. But vaccine demand is hard to equal to 0. Under this situation, the government should try to improve the vaccine effectiveness to minimize the social cost. When R_0 is higher, $f^{G*}=1$. Diseases are very infectious, which is easy to lead to a disease outbreak. The socially optimal situation is that everyone receive vaccination. But $f^{M*}=1-\beta$. The coverage is restricted by the free-riding consumers. The government could make some demand-side interventions to improve vaccination coverage.

2.6 Conclusion

In this paper we present a multi-period vaccine supply chain model taking into account of among-period demand relations and production uncertainty. Combining vaccination externality with customers' vaccination habits, we consider three types of consumers in our demand model, and derive the multi-period supply decisions and the socially optimal coverage.

Our model highlights the significance of among-period demand relations. Vaccination externality could be positive or negative, depending on vaccine effectiveness. When the critical fraction is less than one, which is always considered in extant studies, demand decreases with the coverage in the last period. This results from positive vaccine effectiveness. It also reminds the manufacturer and the government that the largest coverage is not necessarily the best because a large coverage may lead to extremely low demand in the next period. When the critical fraction is larger than one, demand increases with the coverage in the last period. Because of low vaccine effectiveness, the coverage tends to the highest demand. We also study the multi-period profit-maximizing coverage for the manufacturer and the multi-period socially optimal coverage for the government. We show that both coverages are strongly related to infection cost distribution, which decides coverage convergence. Our results provide the manufacturer with helpful production suggestions and enable the government to make their interventions more efficient.

Chapter 3

Effect of Free-riding Behavior on Vaccination Coverage with Customer Regret

3.1 Introduction

Influenza is a seasonal disease that plagues people almost every year. Worldwide, epidemics are estimated to result in about three to five million severe illnesses, and about 290,000 to 650,000 respiratory deaths annually (WHO 2018a). Every year billions of dollars are spent on influenza epidemic preparedness in order to prevent even greater losses. Preventive vaccination is an important way of fighting against influenza outbreaks. However, the vaccination coverage in population is undesirably low, often below the socially optimal level that maximizes the total social welfare (Blue 2008). If the global immunization coverage improves, an additional 1.5 million deaths could be avoided (WHO 2018b).

On the demand side, the free-riding behavior is an important cause of the low vaccination coverage. Herd immunity means that in a population where a large number of individuals are immune, chains of infections are likely to be disrupted, which stops or slows the spread of a disease (Merrill 2015). Vaccination not only makes the vaccinated people immune to an infection, but also indirectly protects the non-vaccinated people, who are called free riders (Fine et al. 2011). When more and more people want to benefit from being free riders, the vaccination coverage will become lower and lower. This is an inevitable problem in the vaccine market.

We consider customer regret in the vaccination demand model when formulating customers' free-riding behavior. The value of the coefficient of customer regret affects the proportion of free riders in the population. The imperfection of vaccination and herd immunity result in the situation where the vaccinated individuals can be infected while the non-vaccinated individuals might be healthy. So customers' decisions made under uncertainty will lead to regret *ex post*. Quiggin (1994) and Braun and Muermann (2004) consider regret only when one's actual utility is worse than the best utility of the alternative choices. In our model regret is related to the coefficient of regret and proportional to the difference between the customers' actual utility and the best utility of the alternative choices. Our study is different from those in the literature in that we do not impose a positive restriction on regret, because we believe that when a person finds the utility of his choice is better than the utility of all the alternative choices, he will feel happy or be prond of his choice. We use negative regret to represent this kind of feeling. In this model, the coefficient of regret affects the proportion of individuals that insist on being free riders. When the coefficient of regret is large enough, we find that the socially optimal vaccination coverage does not encourage individuals to be risk-taking customers anymore.

In order to achieve the socially optimal level of vaccination coverage, the government needs to take some measures to improve the immune coverage; otherwise, it would have to bear a lot of disease-outbreak losses. Adida et al. (2013) find that without government intervention, the vaccination coverage cannot reach the socially optimal level and show that a simple fixed subsidy could help achieve the optimal coverage. Arifoğlu et al. (2012) set the vaccine market as a game model between the customers and the manufacturer, and compare the efficiency of government interventions on either the supply side or the demand side. Our study examines government's subsidy allocations on both the supply and demand sides with consideration of customer regret. Our mechanism could help the market to achieve the largest equilibrium coverage, which is applicable even when the government's budget is limited.

3.2 Literature Review

Vaccination is an important part of a public medical system, and related to the social benefit. Brito et al. (1991), Philipson (2000) and Geoffard and Philipson (1997) consider the health economic issues arising from vaccination and find that the vaccination coverage is below the socially optimal level. Many operations management researchers focus on the optimization of the vaccine supply chain (Wu et al. 2005, Kornish and Keeney 2008, Cho 2010). Arifoğlu et al. (2012) study the impact of inefficiency on both the supply and demand sides considering rational customer behavior. Many supply-side papers (Mamani et al. 2013, Deo and Corbett 2009) find that production uncertainty and insufficient incentives for vaccine manufacturers could be the main causes of the low coverage. Duijzer et al. (2018) mention that another uncertainty is related to the fluctuations in vaccination demand. Moreover, the free-riding behavior on the vaccination demand side has not been fully concerned in the vaccine market. Ibuka et al. (2014) design an experimental study that the probability of vaccination acceptance by non-vaccinated people decreases with observed vaccination coverage within the population, indicating that the free-riding behavior truly exists in an influenza vaccine market. Bauch and Earn (2004) and Reluga et al. (2006) study the free rider problem in a vaccine market through game theory to relate population-level demand to decision-making by individuals. Deo and Corbett (2009) study the effect of the vaccine price on the vaccination coverage in the population. These papers believe that free riders truly exist and make the vaccination coverage below the optimal level, but few of them analyze which effects influence the proportion of free riders and how individuals' idea of being free rider affects the vaccination coverage. We believe that, because of the negative externality, free riders would be more in the actual situation than in the former models and the number of free riders is related to the customer regret. Individuals will compare the cost of taking vaccines with the possible loss of being free riders when making decisions. We consider individuals, under customer regret, still tend to be free riders when the infection loss is not much more than the cost of vaccination. We set this influence as customer regret in the demand model. The coefficient of regret influences the willingness of customers to be free riders, thereby influencing the vaccine market coordination.

Self-interested customers want to maximize their expected utility, consisting of economic utility and emotional utility, i.e., regret. There are some papers about customer regret. Bell (1982) develops the regret theory and finds that by explicitly incorporating regret, expected utility theory not only becomes a better descriptive predictor, but also may become a more convincing guide for prescribing behavior to decision makers. Quiggin (1994) derives a number of special cases in which regret theory is equivalent to other well-known theories of choice under uncertainty. Besides, Braun and Muermann (2004) consider customer regret in insurance decision making. Muermann et al. (2006) and Michenaud and Solnik (2008) apply regret to portfolio and investment choices. Filiz-Ozbay and Ozbay (2007) and Engelbrecht-Wiggans and Katok (2008) connect regret with auction issues, and Perakis and Roels (2008) study regret in a newsvendor model. In operations management area, Nasiry and Popescu (2012) explore the effects of anticipated regret on consumer decisions and firms' profits and policies in an advance selling context where buyers have uncertain valuations. Özer and Zheng (2015) study sellers' optimal pricing and inventory strategies with the effects of anticipated regret. Jiang et al. (2016) and Kuang and Ng (2018) consider the competitive context under customer regret. We consider customer regret in the vaccine market. Because of the imperfection of vaccination and herd immunity, customers' decisions made under uncertainty may lead to regret ex post. We think that customers in a vaccine market would anticipate this regret and take anticipated regret into consideration the same as those in other demand markets.

A low vaccination coverage is a matter of great concern to the government. Geoffard and Philipson (1997) show that the market competition, by itself, cannot eradicate an infectious disease from the population. They study several government intervention strategies and find that, in a perfect market, price strategy can eradicate the disease, while a monopoly manufacturer has an incentive to keep the disease alive. Mamani et al. (2012) consider the costs and benefits of the general customers, as well as the vaccine producers, to derive the total social surplus. They find that, without government subsidy, an oligopolistic market could not achieve the socially optimal coverage, but with the government subsidy the market could reach the optimal level. Mamani et al. (2008) study several types of contracts with the incentive of maximizing the benefits of government and manufacturers at the same time. And they show that the cost-sharing contract can optimize the coordination between the government and manufacturers. Arifoğlu et al. (2012) analyze the inefficiency on the vaccination supply and demand sides, and highlight the interventions on both sides. They suggest that combining demand-side intervention (Brito et al. 1991) and supply-side intervention (Chick et al. 2008) could coordinate the entire supply chain. Our total utility model is similar to the surplus model of Mamani et al. (2012), but we consider customer regret in the model and get some new findings. We find that both the manufacturers' inaccurate estimation of the coefficient of regret and incomplete competition on the supply side will result in disequilibrium between the supply and demand sides. Giving reasonable subsidies to the supply and demand sides to achieve the equilibrium coverage is the most effective way of intervention to achieve the optimal coverage. Then we present the subsidy allocation mechanism on both sides, which is also applicable even when the government's budget is limited.

3.3 Basic Model

In this section, we present the components of our model and discuss the assumptions.

3.3.1 Epidemiology Model

In this study, we use a compartmental model in epidemiology (Kermack and McKendrick 1927). This model is always used to predict the spread properties of various types of epidemics, such as influenza, smallpox, and measles (Bauch et al. 2003, Hill and Longini Jr 2003). The model varies a bit among different kinds of epidemics. In this study, we use the flu-related data to simulate, so we only describe the model which is always used to predict the dynamics of flu, that is the SIR model without involving vital dynamics (Hethcote 2000). This model consists of three compartments: *susceptible* (S), *infectious* (I), and *recovered* (R). These variables (S, I and R) represent the number of susceptible, infected and recovered (or immune) individuals respectively.

Referring to Longini et al. (1996), we consider the vaccine is not perfect and set the situation where the vaccinated people can still be infected. We use ϕ to denote the effectiveness of the vaccine, including the susceptibility and infectiousness effects (Chick et al. 2008). Obviously, $0 \leq \phi \leq 1$. When the vaccine is perfect, $\phi = 1$. Otherwise, $\phi = 0.9$ is also a reasonable estimate for seasonal influenza vaccines (Weycker et al. 2005).

We assume that every individual gets the same information and uses it to make his own choice. We consider the population as a whole and define f as the vaccination coverage, i.e., proportion, of the total population. Infection probabilities are different for the vaccinated and non-vaccinated people (Anderson and Hanson 2005, Hughes et al. 2002). $P(f)$ and $p(f)$ are the infection probabilities for non-vaccinated and vaccinated people, respectively. And $r(f)$ is the infection probability of the entire population (Bauch and Earn 2004). Similar to Adida et al. (2013), it is easy to get:

$$r(f) = fp(f) + (1 - f)P(f) \tag{3.1}$$

and

$$P(f) = \frac{r(f) - fp(f)}{1 - f}. \tag{3.2}$$

From the epidemiology literature, $r(f)$ has an estimation in (3.3). We use this equation to obtain our results in the following.

$$r(f) = \begin{cases} 0 & \text{if } f > \frac{R_0 - 1}{\phi R_0}, \\ 1 - \phi f - \frac{1}{R_0} & \text{otherwise.} \end{cases} \tag{3.3}$$

In (3.3), R_0 represents the basic reproduction number and is a measure of the infectiousness of a disease (Anderson and May 1992, Murray 1993). When the coverage achieves $F = \frac{R_0 - 1}{\phi R_0}$, the infection probability of the whole population decreases to zero. In epidemiology, F is called the critical vaccination fraction. It represents the minimum level of vaccination coverage necessary for providing herd immunity, a situation that arises when the vaccination level is sufficiently high so that it eliminates the disease from the population completely (Anderson and May 1985). And we also provide an estimation of $p(f)$ in Appendix B.

As mentioned above, our model has several assumptions: (I) Similar to Brito et al. (1991), we assume the vaccine effectiveness ϕ, vaccination coverage f, and infection probabilities $p(f)$ and $P(f)$ are common knowledge to all the social groups. (II) Both $p(f)$ and $P(f)$ are continuous and non-increasing in f; otherwise, individuals do not have any incentive to take the vaccine. (III) We assume that $r(f)-p(f)$ is a non-increasing function of f. This implies that as f increases, the infection probability gap between the vaccinated people and the whole population decreases. When f reaches the critical vaccination fraction, the gap vanishes. (IV) We assume that $f(r(f)-p(f))$ is a concave function of f in $[0, \bar{F}]$, where $\bar{F} = min\{F, 1\}$. This assumption is commonly made in economics to ensure that the revenue is a concave function and consistent with the extensive numerical testings in a real-world setting (Mamani et al. 2012).

3.3.2 Demand Model with Customer Regret

Customer utility without regret. We model that the vaccine market consists of profit-maximizing manufacturers, self-interested customers, and the society. Manufacturers produce the vaccines and sell them directly to the customers. Any infection will bring an inevitable loss to society. Later we will consider the government's intervention in the market.

We consider the population as a whole, in which each healthy individual enjoys utility $\bar{V}$. The health outcome of an individual can be one of the four categories: (i) vaccinated and healthy, (ii) vaccinated and infected, (iii) non-vaccinated and healthy, and (iv) non-vaccinated and infected, each with some probability. Among these four results, the healthy non-vaccinated individuals are successful free riders and the infected non-vaccinated individuals are unsuccessful free riders. The disutility of taking the vaccine is W per person. An infected individual will have disutility Lu (Meltzer et al. 1999, Galvani et al. 2007), including all direct and indirect losses from an infection. Similar to Mamani et al. (2012), we assume that u follows a uniform distribution between 0 and 1, and L represents the largest disutility from an infection.

We have the following assumptions about the vaccine supply chain: (V) At the beginning of the influenza season, production has been finished and the vaccine becomes available to the customers that will decide whether or not to take it. (VI) The largest disutility from an infection L is larger than the disutility of taking the vaccine W; otherwise, no one will be willing to take the vaccine. (VII) The utility $\bar{V}$ and disutility W are common knowledge for the customers, and each individual knows his own infection disutility Lu. Utility in Figure 3.1 shows the customer utility of different groups without considering customer regret.

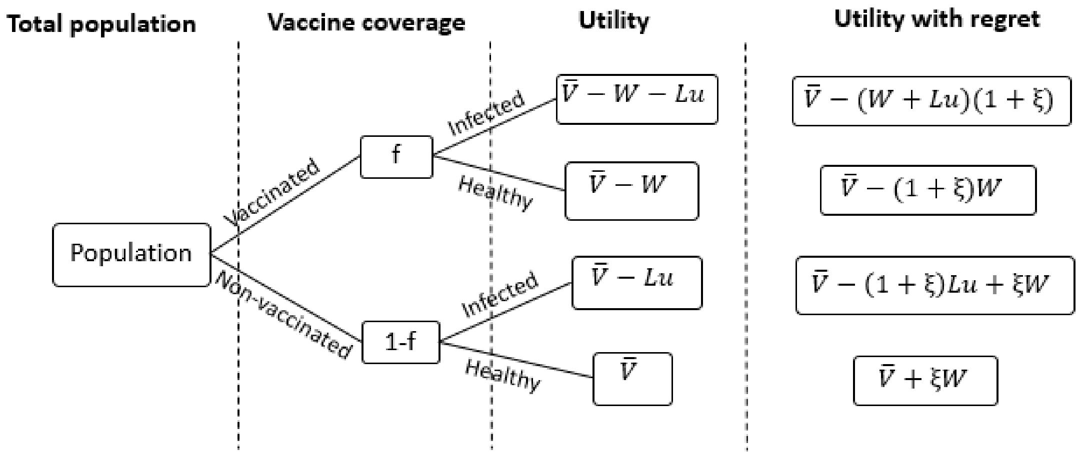

Figure 3.1: Customer vaccination utility with regret

Customer utility with regret. Individuals will compare the cost of vaccination with the probable loss of being free riders when making decisions. We consider individuals, with the idea of gambler, still tend to be free riders when the infection loss without regret is not much more than the cost of vaccination without regret. We set this influence as a coefficient of customer regret to affect the vaccine market coordination. Following the Regret Theory (Bell 1982, Loomes and Sugden 1982), we assume that customers are strategic and emotionally rational. Given the expected utility of taking and not taking the vaccine, customers make choices in order to maximize their own utility consisting of economic utility and emotional utility, i.e., regret. Following Quiggin (1994) and Braun and Muermann (2004), we consider regret is proportional to the disutility of not having chosen the ex post best forgone alternative. Our model is different from former models that we have not set positive restriction on regret, because we think that when a person finds the cost of his choice is less than the cost of the alternative choices, he will feel happy or pride of his choice. We use the negative regret to represent this kind of feelings. And customers only have two choices, taking the vaccine or not. Then in other words, regret in our model is proportional to the difference between one's actual utility and the ex post best utility of the other alternative choices. We will analyze the relationship between the customer regret and the proportion of free riders later. ξ, which is between 0 and 1, is the coefficient of customer regret. The utility with customer regret consideration is also depicted in Figure 3.1. The maximum utility of non-vaccinated people is $\bar{V}$, then for infected vaccinated individuals, the regret value is $\xi(W + Lu)$, their total utility becomes $\bar{V} - (1 + \xi)(W + Lu)$. Similarly, for healthy vaccinated people, the regret value is ξW, total utility is $\bar{V} - (1+\xi)W$. On the other hand, the maximum utility of vaccinated individuals is $\bar{V} - W$, then for infected non-vaccinated people, the regret value is $\xi(Lu - W)$ and total utility is $\bar{V} - Lu - \xi(Lu - W)$. The regret value for healthy non-vaccinated people is $-\xi W$, and their utility is $\bar{V} + \xi W$.

Marginal customers. Customers that choose to take the vaccine will have a lower probability of getting infection than those customers who do not. But because of the vaccine's imperfection, vaccinated individuals, albeit less likely, could be infected. Vaccinated individuals will be infected with probability $p(f)$ and enjoy the utility $\bar{V} - (1 + \xi)(W + Lu)$, where f is the vaccination coverage. They will be healthy with probability $1 - p(f)$ and enjoy the utility $\bar{V} - (1 + \xi)W$. Then the expected utility of getting vaccinated is $\bar{V} - (1 + \xi)(W + Lup(f))$. On the other hand, non-vaccinated individuals will be infected with probability $P(f)$ and enjoy the utility $\bar{V} - Lu - \xi(Lu - W)$. They will be healthy with probability $1 - P(f)$ and enjoy the utility $\bar{V} + \xi W$, yeilding the expected utility for non-vaccinated consumers as $\bar{V} - LuP(f)(1 + \xi) + \xi W$. Therefore, an individual with the infection disutility $L\hat{u}$ will not take the vaccine unless:

$$\bar{V} - (1 + \xi)(W + L\hat{u}p(f)) > \bar{V} - L\hat{u}P(f)(1 + \xi) + \xi W.$$

Lemma 4. *In equilibrium, for given W and L, if an individual whose infection utility is $\hat{u}$ does not take the vaccine, then none of the individuals whose infection utility is less than $\hat{u}$ will take the vaccine. Then we can find that for the marginal individual that is indifferent to taking the vaccine or not as follows:*

$$\bar{V} - (1+\xi)(W + Lup(f)) = \bar{V} - LuP(f)(1+\xi) + \xi W. \tag{3.4}$$

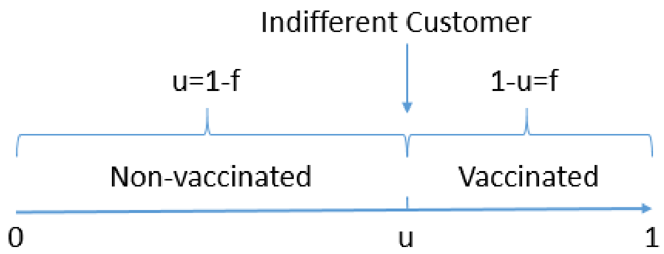

Figure 3.2: Infection utility and the coverage

As Figure 3.2 shows, the infection utility u follows a uniform distribution from 0 to 1. Then the market achieves equilibrium and the coverage f will have a relationship with the u of the marginal customer. That is

$$u = 1 - f. \tag{3.5}$$

For simplicity, we set $w = \frac{W}{L}$ and $\bar{v} = \frac{\bar{V}}{L}$ to denote the unit normalized vaccine price and utility, respectively. With (3.2) and (3.5), (3.4) could be transformed into:

$$w = \frac{1+\xi}{1+2\xi}(r(f) - p(f)). \tag{3.6}$$

Robbins and Lunday (2016) emphasize that the customers' subsequent vaccine selection decision problem must be considered with the vaccine price. (3.6) illustrates the relationship between the vaccine price and the customers' selection. And f in (3.6) denotes the coverage that the customers are willing to achieve. In Figure 3.3, we set a fixed and reasonable value for w (Weycker et al. 2005, CDC 2009) and depict the relationship between the coverage and ξ. This value of ξ is an estimate of the entire social group.

Lemma 5. *As the coefficient of regret ξ increases, the proportion of free riders in the whole population increases, resulting in the coverage decreases.*

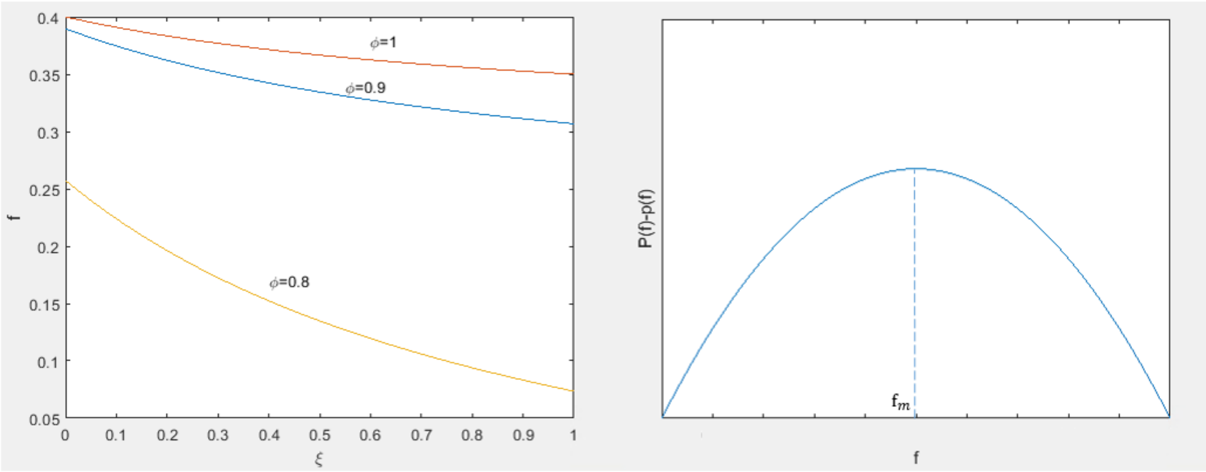

Figure 3.3: The equilibrium coverage as a function of ξ

We illustrate Lemma 5 on the left of Figure 3.3, and give the proof in Appendix B. Self-interested customers want to improve their utility, then more and more individuals tend not to take the vaccine. This means even if the vaccine price remains the same, as ξ increases, the proportion of free riders will become more. We believe no one will insist on being a free rider when his infection loss is much more than the cost of vaccination. Customers tend to be free riders based on his infection utility and the probability of being a successful free rider.

This figure also shows that as the effectiveness of the vaccine declines, the coverage will be more and more affected by ξ. The vaccine effectiveness decides the probability of the vaccinated customers getting infected, i.e., $p(f)$. When the vaccine effectiveness decreases, the expected utility of the vaccinated individuals decreases. Then customers tend not to take the vaccine and the coverage decreases. But this rule is not always true, it depends on the formulated functions of $r(f)$ and $p(f)$ we use.

Lemma 6. *$P(f) - p(f)$ is a concave function of f in $[0, \bar{F}]$.*

We illustrate Lemma 6 on the right of Figure 3.3. When $f = 0$ or $f = \bar{F}$, $P(f)$ is equivalent to $p(f)$ and $P(f)-p(f)$ is zero. When f is between them, $P(f)-p(f)$ will be positive because non-vaccinated individuals have a larger probability of getting infection. Then, as f increases from 0 to f_m, $P(f)-p(f)$ increases. When f increases between f_m and 1, $P(f) - p(f)$ decreases. We also use the formulated functions to prove this lemma in Appendix B.

3.4 The Total-utility Problem

In this part, we consider the utility for different parties and combine them into a total-utility problem. We consider three groups: manufacturers, customers and the society. We accrue the utility of different parties as the total social welfare and maximize it, thereby getting the optimal vaccination coverage.

Customers' problem. In this part, we consider the utility of vaccinated customers and non-vaccinated customers separately. As in Figure 3.2, customers with infection utility from $1-f$ to 1 would choose to take the vaccine. The accumulated utility for them is:

$$\text{Vaccinated utility} = \int_{1-f}^{1} [\bar{V} - (1+\xi)(W + Lup(f))]du. \tag{3.7}$$

On the other hand, customers with infection utility from 0 to $1-f$ would not take the vaccine. The accumulated utility for them is:

$$\text{Non-vaccinated utility} = \int_{0}^{1-f} [\bar{V} - LuP(f)(1+\xi) + \xi W]du. \tag{3.8}$$

Manufacturers' problem. Let the production cost of a vaccine be T. Then the unit normalized cost of production is $t = \frac{T}{L}$. Manufacturers produce the vaccine based on the coverage f and would like to maximize the expected profit. Thus, the manufacturers' problem is to maximize:

$$\text{Manufacturers utility} = (w-t)f. \tag{3.9}$$

The society's problem. In addition to the infection cost borne by the infected customers, we also consider another cost that may accrue on the society as a whole, including the loss of work time, the burden on the public health system, and so on (Mamani et al. 2012). We assume that every infected customer (including vaccinated and non-vaccinated) poses a loss of λL to the society. A fraction $r(f)$ of the total population might get infected, so we can get the unit societal utility:

$$\text{Societal utility} = -\lambda r(f). \tag{3.10}$$

3.4.1 Total Social Welfare

Similarly, we set $\bar{v} = \frac{\bar{V}}{L}$ and normalize (3.7) and (3.8). Then we combine these unit normalized equations with (3.9) and (3.10) together to get the total social welfare:

$$\begin{aligned}\text{Total social welfare} &= \bar{v} - tf - (1+\xi)(p(f)\frac{1-(1-f)^2}{2} + P(f)\frac{(1-f)^2}{2}) \\ &\quad -2\xi wf + \xi w - \lambda r(f). \qquad (3.11)\end{aligned}$$

Considering $\bar{v}$ as a constant, we maximize (3.11), which is equivalent to minimizing SC:

$$\begin{aligned}\min SC &= tf + (1+\xi)\frac{(1-f)r(f) + fp(f)}{2} + 2\xi wf - \xi w + \lambda r(f) \\ &= tf + (\lambda + \frac{1+\xi}{2(1+2\xi)})r(f) + \frac{\xi(1+\xi)}{1+2\xi}p(f) \\ &\quad + \frac{(2\xi-1)(\xi+1)}{2(1+2\xi)}f(r(f) - p(f)). \qquad (3.12)\end{aligned}$$

Proposition 10. *For $\xi < 0.5$, let $f = \widetilde{f}$ be the solution of:*

$$t - (\lambda + \frac{1+\xi}{2(1+2\xi)})\phi - \frac{\xi(1+\xi)}{1+2\xi}\phi\mu(1-\phi) + \frac{(2\xi-1)(\xi+1)}{2(1+2\xi)}\frac{d(f(r(f)-p(f))}{df} = 0.$$

Then the equilibrium level of vaccination coverage can be written as

$$f^* = \begin{cases} 0 & \text{if } t > m_2, \\ \widetilde{f} & \text{if } m_1 \le t \le m_2, \\ min\{\frac{R_0-1}{\phi R_0}, 1\} & \text{otherwise,} \end{cases}$$

where

$$m_1 = (\lambda + \frac{1+\xi}{2(1+2\xi)})\phi + \frac{\xi(1+\xi)}{1+2\xi}\phi\mu(1-\phi) + \frac{(2\xi-1)(\xi+1)}{2(1+2\xi)}\bar{F}(\phi + p'(\bar{F})),$$

$$m_2 = (\lambda + \frac{1+\xi}{2(1+2\xi)})\phi + \frac{\xi(1+\xi)}{1+2\xi}\phi\mu(1-\phi) - \frac{(2\xi-1)(\xi+1)}{2(1+2\xi)}(\frac{R_0-1}{R_0} - P(0)).$$

Figure 3.4 plots the optimal coverage of different values of the coefficient of regret. $\xi = 0$ means we do not consider customer regret at all, and $\xi = 0.1$ illustrates the results of Proposition 10. In this figure, t is mainly influenced by L, because $t = \frac{T}{L}$, where T is far less than L. In the first case, when the infection cost L is high, i.e., $t < m_1$, the socially optimal coverage achieves the critical vaccination fraction, at which the probability of getting infection for every individual is all equal to zero. In

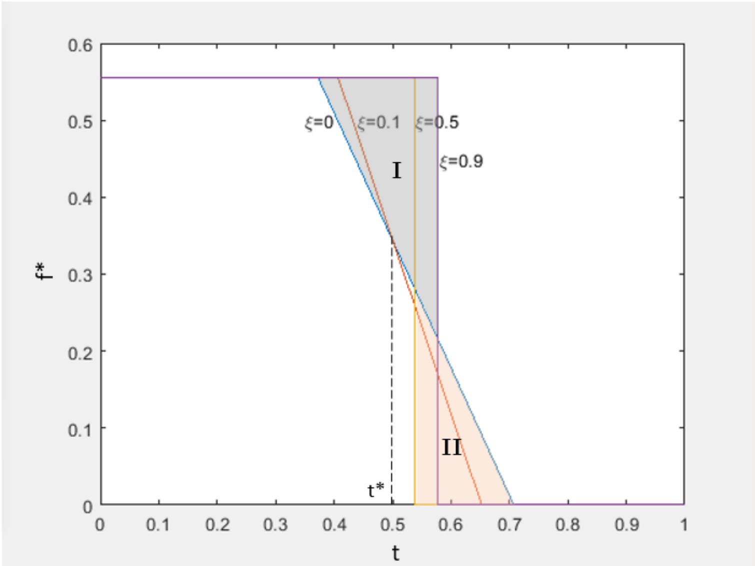

Figure 3.4: The socially optimal coverage ($\phi = 0.9$)

the second case, when the infection cost L is low, i.e., $t > m_2$, the market would best not to produce and sell the vaccine at all. In the third case, when t is between these two extreme values, some people will take the vaccine, but the coverage does not achieve the critical vaccination fraction. As a whole, the socially optimal coverage doesn't increase as the infection cost decreases. Referring to some data of influenza (Weycker et al. 2005), t always cannot reach the extremely high level, i.e., $t > m_2$. However, with government intervention, some medical social expenses can reimburse most of the medical expenses. Then, the second or the third case could happen. This kind of welfare could provide protection for people, but, for epidemic diseases, high medical welfare would decrease people's willingness of taking the vaccine. When the coverage is very low, disease outbreak might happen. Therefore, we suggest that the government should control the reimbursement system for medical expenses for epidemic diseases, so that t will not reach an excessively high level.

Figure 3.4 also shows the difference of the socially optimal coverage between considering customer regret and not considering. We have known that the increase of ξ will decrease customers' willingness of taking the vaccine, thereby decreasing the coverage that customers are willing to achieve. However, the decrease of f will increase both the infection probability for vaccinated individuals and non-vaccinated individuals.

When the infection cost is high and t is relatively low, i.e., in area I, the optimal coverage under customer regret is larger than or equal to the coverage without customer regret. The socially optimal coverage under regret suggests individuals should have a higher vaccination coverage. As t increases, i.e., in area II, the optimal coverage with regret will finally be below the optimal coverage without it. The socially optimal coverage under regret encourages fewer customers to take the vaccine. Therefore, we can get Proposition 11.

In Figure 3.4, $\xi = 0.5$ and $\xi = 0.9$ illustrate Proposition 11. When the customer regret reaches or exceeds 0.5, the optimal coverage would change a lot. When the infection cost is high, i.e., $t > \widetilde{t}$, the market would not produce the vaccine at all and make the coverage equal to zero. When the infection cost is low, i.e., $t \leqslant \widetilde{t}$, the socially optimal coverage is the critical vaccination fraction. The third case in Proposition 10, in which the coverage is between zero and the critical vaccination fraction, does not exist anymore.

Proposition 11. *For $\xi \geq 0.5$, let $t = \widetilde{t}$ be the solution of:*

$$\widetilde{t} = \phi(\lambda + \frac{1+\xi}{2(1+2\xi)}(1 + 2\mu\xi(1-\phi)).$$

Then,

$$f^* = \begin{cases} 0 & if\, t > \widetilde{t}, \\ min\{\frac{R_0 - 1}{\phi R_0}, 1\} & if\, t \leqslant \widetilde{t}. \end{cases}$$

In this situation, the socially optimal coverage does not encourage individuals to be risk-taking vaccinated customers anymore. Customers take the vaccine and make the coverage reach the critical vaccination level, in which the whole population is in a safe state; or do not take the vaccine at all when t is occasionally high. Customers seem to be more united. With the increase of regret value, more customers should take the vaccine and help to achieve the critical vaccination coverage, i.e., in area I of Figure 3.4, people do not voluntarily take the vaccine to reach the critical vaccination fraction when people do not consider the regret value or the coefficient of regret is small, but they do when the regret value increases.

For different vaccine effectiveness, the range of different influences will be different. We show the optimal coverages of different vaccine effectiveness, i.e., ϕ, in

Figure 3.5. This figure plots the situation of $\phi = 0.8$ on the left and $\phi = 1$ on the

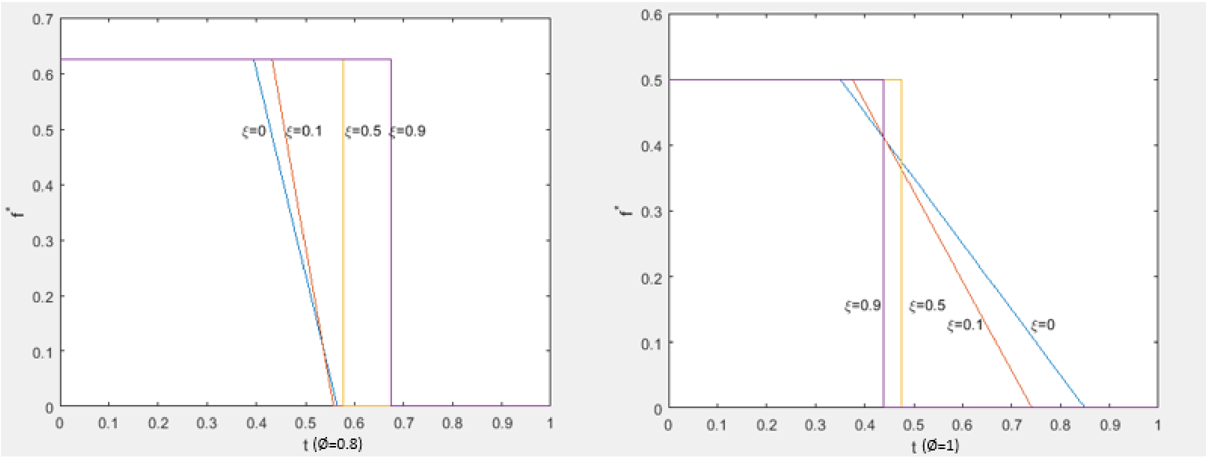

Figure 3.5: The socially optimal coverage ($\phi = 0.8$ and 1)

right. From these two graphs, we can get Proposition 12.

Proposition 12. *For ϕ is an uncertain value between 0 and 1, sometimes the optimal coverage under a higher coefficient of regret suggests a higher coverage, sometimes a lower coverage.*

As the effectiveness of the vaccine decreases, the range of the third case in Proposition 10 becomes smaller. Thereby, the optimal coverages for $\xi = 0$ and $\xi = 0.1$ become similar to those for $\xi = 0.5$ and $\xi = 0.9$. Under this vaccine effectiveness, for a wide range of t, the optimal coverage under higher coefficient of regret suggests more individuals to take the vaccine and to achieve the critical vaccination fraction. We can get the special case of $\phi = 1$ on the right of Figure 3.5. This figure plots that, when the vaccine is perfect, the optimal coverage of $\xi = 0.9$ will be less than the coverage of $\xi = 0.5$.

3.5 Government Intervention

In this section, we consider self-interested customers and profit-maximizing manufacturers. We find that both manufacturers' inaccurate estimation of ξ and incomplete competition in the supply market will result in disequilibrium between the supply and demand. Therefore, we present the subsidy allocations on both supply and demand sides. Our mechanism could help the market to achieve the largest equilibrium coverage, which is also applicable even when the government's budget is limited.

3.5.1 Demand Market

In the previous model, we estimate the value of the coefficient of regret and assume every party knows it. But, in real life, if the government does not make specific investigations and report them, manufacturers might not know the specific coefficient of customer regret. Then, in this section, we consider an incomplete-information market, where the manufacturers may not know the actual coefficient of customer regret. We set ξ_d as the actual coefficient of customer regret and the customers will voluntarily achieve a coverage of f_d.

Referring to (3.4), we get Lemma 7.

Lemma 7. *The marginal-customer function under incomplete-information market would become:*

$$w = \frac{1+\xi_d}{1+2\xi_d}(r(f_d) - p(f_d)). \tag{3.13}$$

3.5.2 Oligopolistic Supply Market

We consider the vaccine market as a Cournot competition among n identical vaccine manufacturers (Mamani et al. 2012) and apply the concept of the rational expectation Cournot equilibrium (Katz et al. 1985). f_{oi} is the market share of producer i. Because we consider n manufacturers are identical, they will have identical w_i and t_i. We assume manufacturers share the same estimation of the coefficient of customer regret, i.e., ξ_s, but this estimation might not be accurate. Then it is easy to prove $f_{o1} = f_{o2} = ... = f_{on} = \frac{f}{n}$. The ith manufacturer faces the following decision problem:

$$\max_{f_i} \pi_i = (w_i - t_i)f_i = (\frac{1+\xi_s}{1+2\xi_s}(r(f) - p(f)) - t)f_i. \tag{3.14}$$

Lemma 8. *In an oligopolistic vaccine market with n identical producers engaged in a Cournot competition, the total market coverage is given by*

$$f_n = \begin{cases} 0 & \text{if } t > \frac{1+\xi_s}{1+2\xi_s}(\frac{R_0-1}{R_0} - p(0)), \\ \hat{f} & \text{otherwise,} \end{cases}$$

where $f = \hat{f}$ is the solution of:

$$-t + \frac{1+\xi_s}{1+2\xi_s}(r(f) - p(f)) + \frac{f}{n}\frac{1+\xi_s}{1+2\xi_s}(r'(f) - p'(f)) = 0.$$

3.5.3 Government Subsidy

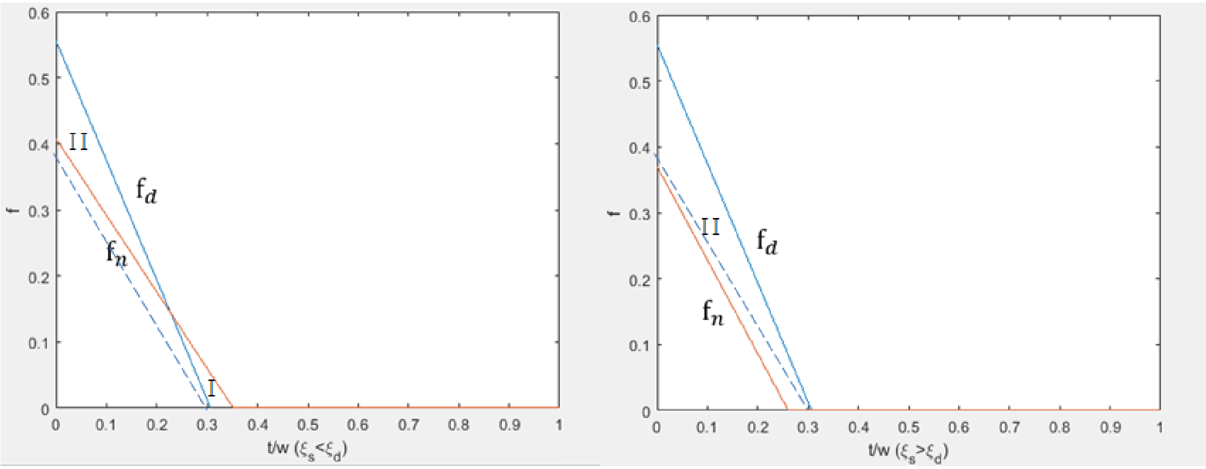

Figure 3.6: The relationship between f_d and f_n

We consider an incomplete-information market where the actual coefficient of customer regret is ξ_d and n manufacturers have an estimation of customer regret ξ_s. In Figure 3.6, we depict the self-interested customers' coverage f_d and the profit-maximizing manufacturers' coverage f_n, under the situation that $\phi = 0.9$. When manufacturers underestimate the coefficient of regret, i.e., $\xi_s < \xi_d$, the situation is depicted on the left of this figure. And the situation of overestimation, i.e., $\xi_s > \xi_d$, is depicted on the right of this figure. For f_d, we assume that for critical conditions where $w = c$, manufacturers will still be willing to produce to meet the demand in order to increase the market share.

Proposition 13. *The government should reduce medical subsidies and keep other medical expenses reimbursement, like medical insurance, under control. If the infection cost L is increased, then t and w will decrease, and the coverage will increase.*

Figure 3.6 shows that both customers' willingness to pay and manufacturers' willingness to produce decrease as t or w increases. When t or w achieves an extremely high level, the coverage decreases from the critical vaccination fraction and even to zero. This situation easily leads to disease outbreak. Therefore, we have Proposition 13.

Proposition 14. *When manufacturers underestimate the coefficient of regret, i.e.,* $\xi_s < \xi_d$*, there will be two kinds of situations:* $f_d > f_n$ *and* $f_d < f_n$*. When manufacturers overestimate the coefficient of regret, i.e.,* $\xi_s > \xi_d$*, there is only* $f_d > f_n$*.*

Area I, i.e., $f_d < f_n$, in Figure 3.6 represents that manufacturers are willing to produce, but self-interested customers are not willing to pay. Referring to Lemma 5, a higher ξ will result in a lower coverage. This gap is resulted from the manufacturers' underestimation of customer regret, i.e., $\xi_s < \xi_d$. Because manufacturers suppose a lower coefficient of regret, the supply will be higher than the actual demand. Area II, i.e., $f_d > f_n$, on the left and the right of Figure 3.6 represents the situation that customers are willing to buy, but manufacturers are not willing to produce anymore. This gap in the left figure is resulted from the limited number of manufacturers on the supply side. Except this reason, the gap in the right figure is also resulted from the manufacturers' overestimation of customer regret, i.e., $\xi_s > \xi_d$. In this situation, the government could encourage more vaccine manufacturers to enter the market and make the competition more complete. Besides, if the manufacturers could estimate the customer's regret value more accurately, the inefficiency of Areas I and II will both be reduced and Area I could even be eliminated. Therefore, both manufacturers' inaccurate estimation of the coefficient of regret and incomplete competition in the supply market will result in disequilibrium status between the supply and demand. And more accurate estimation of ξ for manufacturers and more complete competition in supply market could help balance the supply and demand.

Government Subsidy. Without government intervention, the actual vaccination coverage will be $min\{f_d, f_n\}$. The dotted line in Figure 3.6 denotes the situation of $\xi_s = \xi_d$. The actual coverage of $\xi_s < \xi_d$ is better than the coverage of $\xi_s = \xi_d$ and the actual coverage of $\xi_s > \xi_d$ is worse than the coverage of $\xi_s = \xi_d$. Therefore, if the government know the actual value of ξ_d, it should announce it to the manufacturers to improve coverage if the probability of $\xi_s > \xi_d$ is more than the probability of $\xi_s < \xi_d$, and not announce it to the manufacturers, otherwise.

As in Figure 3.6, Area I represents that the manufacturers are willing to produce, but utility-maximizing customers are not willing to pay. Giving subsidy to customers could achieve the demand-supply equilibrium. Area II shows that the customers are willing to buy, but the manufacturers are not willing to produce. Then giving subsidy to manufacturers could help to achieve the demand-supply equilibrium. The suggestions that we have made above could make the vaccine market cooperation more efficient to achieve the demand-supply equilibrium, but could not help the coverage to achieve the socially optimal level. At this time, both the customers and manufacturers have no incentive to increase the coverage, we need to give subsidies to both of them to achieve the socially optimal coverage.

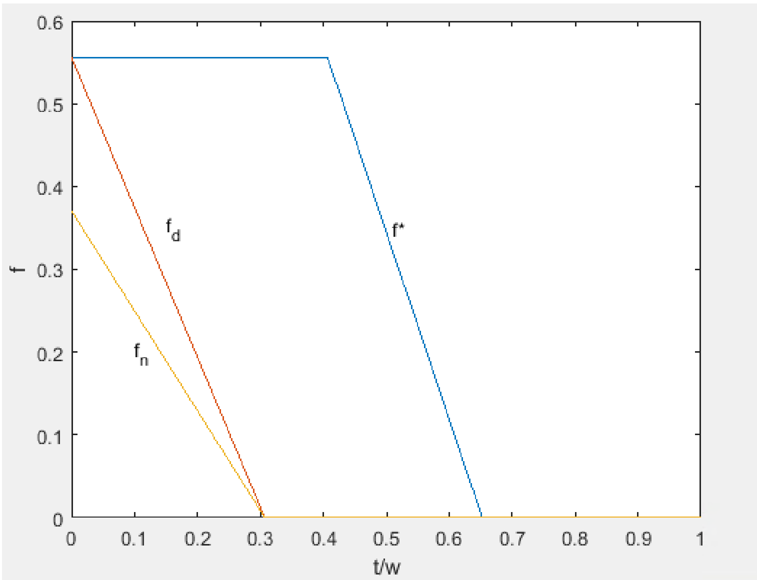

Figure 3.7: The socially optimal coverage

When we do not have any related information, the probability of $\xi_d < 0.5$ is equal to the probability of $\xi_d > 0.5$. We set a situation of $\xi_d < 0.5$, where the government knows the actual ξ_d and announces it to the manufacturers, to be an example in Figure 3.7.

Based on Proposition 10 and Lemma 7, we can get the subsidy giving to the customers.

$$s = \begin{cases} 0 & \text{if } w > m_2, \\ w - \frac{1+\xi_d}{1+2\xi_d}(r(f^*) - p(f^*)) & \text{if } m_1 \le w \le m_2, \\ w - \frac{1+\xi_d}{1+2\xi_d}(r(\bar{F}) - p(\bar{F})) & \text{otherwise,} \end{cases}$$

where

$$m_1 = (\lambda + \frac{1+\xi}{2(1+2\xi)})\phi + \frac{\xi(1+\xi)}{1+2\xi}\phi\mu(1-\phi) + \frac{(2\xi-1)(\xi+1)}{2(1+2\xi)}\bar{F}(\phi + p'(\bar{F})),$$

$$m_2 = (\lambda + \frac{1+\xi}{2(1+2\xi)})\phi + \frac{\xi(1+\xi)}{1+2\xi}\phi\mu(1-\phi) - \frac{(2\xi-1)(\xi+1)}{2(1+2\xi)}(\frac{R_0-1}{R_0} - P(0)).$$

Then every individual could get $1/N$ of this subsidy, where N is the number of people of this population.

Based on Proposition 10 and Lemma 8, we can get the subsidy giving to the manufacturers.

$$s = \begin{cases} 0 & \text{if } t > m_2, \\ t - \frac{1+\xi}{1+2\xi}(r(f^*) - p(f^*)) - \frac{f^*}{n}\frac{1+\xi}{1+2\xi}(r'(f^*) - p'(f^*)) & \text{if } m_1 \le t \le m_2, \\ t - \frac{1+\xi}{1+2\xi}(r(\bar{F}) - p(\bar{F})) - \frac{\bar{F}}{n}\frac{1+\xi}{1+2\xi}(r'(\bar{F}) - p'(\bar{F})) & \text{otherwise.} \end{cases}$$

Then every manufacturer could get $1/n$ of this subsidy.

We find different formulation of the socially optimal coverage for different regret coefficient in our model, and we only take the situation of $\phi = 0.9$ and $\xi = 0.1$ as an example. But it is easy to get the suitable subsidy for other situations. Besides, sometimes the government does not have enough money to make the market achieve the socially optimal level. Our mechanism can also make reasonable budget allocation to help the market achieve the largest equilibrium coverage under limited budget. This will help the government to allocate subsidies the most efficient way.

Proposition 15. *Assume the government's budget is B and the coefficient of customer regret is ξ, and before giving subsidy $t = t_0$ and $w = w_0$. Then the subsidy to manufacturers is:*

$$S_m = B \times l_m.$$

The subsidy to customers is:

$$S_c = B \times l_c.$$

where

$$l_m = t_0 - \frac{1+\xi_s}{1+2\xi_s}(r(f) - p(f)) - \frac{f}{n}\frac{1+\xi_s}{1+2\xi_s}(r'(f) - p'(f)),$$

$$l_c = w_0 - \frac{1+\xi_d}{1+2\xi_d}(r(f) - p(f)),$$

$$l_m + l_c = 1.$$

In Proposition 15, f is the equilibrium coverage after giving subsidies.

3.6 Conclusion

To the best of our knowledge, we are the first one to incorporate the customer regret into a vaccine demand model. We formulate the proportion of free riders in the whole population by considering customer regret in the vaccine demand model. We consider that no matter what choices the customers make, they may end up with a feeling of regret or pride, i.e., positive regret or negative regret. The regret will change with the vaccine price and medical expenses, and will also be affected by the coefficient of regret ξ. The higher ξ is, the more individuals tend to be free riders. We find that as the infection cost decreases, the socially optimal coverage will decrease from the critical vaccination fraction. It is because when the medical expenses are low, customers do not enough incentives to take the vaccine. In general, the infection cost will not fall to such a low level. However, it also reminds the government not to provide high welfare to epidemic infection costs, and also to adopt some policies to control the reimbursement of some related medical insurance for this kind of costs.

For different coefficients of customer regret, the socially optimal coverage changes a lot. When the coefficient of regret is large enough, the socially optimal coverage does not encourage individuals to be risk-taking customers anymore, who take the vaccine and still have a probability to be infected. At this time, customers take the vaccine and make the coverage reach the critical vaccination level, in which the whole population is in a safe state; or do not take the vaccine at all. However, the influence of customer regret should be considered with vaccine effectiveness. Sometimes, a higher coefficient of regret suggests a higher vaccination coverage but sometimes a lower coverage.

When we consider customer demand and manufacturer supply, we find that both manufacturers' inaccurate estimation of the coefficient of customer regret and incomplete competition in the supply side will make the disequilibrium between the supply side and the demand side. Manufacturers' underestimation of the coefficient of regret will improve the actual coverage and their overestimation will decrease the coverage. Therefore, we need to compare the probability of underestimation and the probability of overestimation to decide whether the government should announce the actual coefficient to manufacturers.

Finally, we propose a government subsidy policy on both the supply and demand sides. The government provides subsidies to both sides in proportion to its own budget to achieve the most efficient subsidies. This subsidy policy enables the market to achieve the largest equilibrium coverage, which is applicable even when the government's budget is limited.

Chapter 4

Summary and Future Research

In this thesis, we conduct two studies on the vaccine supply chain, considering multi-period vaccine market and customer vaccination regret, respectively. In this section, we summarize these two studies, point out some future research directions, and conclude the overall contributions of the two studies.

In the first study, we present a multi-period vaccine supply chain model taking account of demand relations and production uncertainty. We combine vaccination externality with vaccination habits and include three types of consumers in our demand model. Multi-period supply decisions and socially optimal coverage have also been studied. Our results provide management insights on vaccine supply decisions, government interventions and vaccine coverage.

In the second study, we incorporate the customer regret into a vaccine demand model. We formulate the proportion of free riders in the whole population by considering customer regret in the vaccine demand model. For different coefficients of customer regret, the socially optimal coverage changes a lot. We also propose a government subsidy policy on both the supply and demand sides. This subsidy policy enables the market to achieve the largest equilibrium coverage, which is applicable even when the government's budget is limited.

This thesis provides several interesting avenues for future research. One extension is to consider a more complicated oligopolistic market in our model, where manufacturers have different costs and prices, thereby getting different market shares. Another direction is to consider different groups of individuals. In reality, school children or old people may have a higher priority to get vaccinated. Then the model will be closer to the real situation.

In summary, the two studies capture the customer vaccination behaviors in multi-period market and customer regret. These studies contribute to the efficiency of vaccine supply chain on production decisions and government interventions. In fact, the inefficiency of vaccine supply chain are far more complex. First, there may be more than one manufacturer in the vaccine supply market. They offer different vaccine prices and compete with each other. Second, not all vaccines are ready to use at the beginning of a flu season. Some vaccines are supplied to the market at the middle or the end of a flu season. Thus, a lot of research directions in vaccine supply chain remain to be explored.

Appendix A

Proofs for Chapter 2

Proof of Proposition 1.

$u^m_{t+1} = \frac{w}{P(f_t)-H(f_t)} = \frac{w(1-f_t)}{r(f_t)-H(f_t)}; d_{t+1} = (1-\alpha-\beta)\bar{G}(u^m_{t+1})+\alpha = (1-\alpha-\beta)\bar{G}(\frac{w(1-f_t)}{r(f_t)-H(f_t)})+\alpha.$

Proof of Proposition 2.

$$\frac{d(d_{t+1})}{d(f_t)} = \frac{-w(1-\alpha-\beta)[(r(f_t)-H(f_t))+(1-f_t)(r'(f_t)-H'(f_t))]}{(r(f_t)-H(f_t))^2}\frac{-dG(u^m_t)}{du^m_t}$$

$$= \frac{-w(1-\alpha-\beta)(\phi+\frac{1}{R_0}-1)}{(1-\eta(1-\phi))(1-\phi f_t-\frac{1}{R_0})^2}\frac{dG(u^m_t)}{du^m_t};$$

$$\frac{d^2(d_{t+1})}{df_t^2} = -g(\frac{w(1-f_t)}{r(f_t)-H(f_t)})[\frac{-2w(1-\alpha-\beta)\phi(\phi+\frac{1}{R_0}-1)}{(1-\eta(1-\phi))(1-\phi f_t-\frac{1}{R_0})^3}]-g'(\frac{w(1-f_t)}{r(f_t)-H(f_t)})\frac{w(1-\alpha-\beta)(\phi+\frac{1}{R_0}-1)}{(1-\eta(1-\phi))(1-\phi f_t-\frac{1}{R_0})^2}$$

(1)$\phi > 1-\frac{1}{R_0}$, $\frac{d(d_{t+1})}{d(f_t)} < 0$, $d_{t+1}(f_t)$ is a decreasing function.

(2)$\phi < 1-\frac{1}{R_0}$, $\frac{d(d_{t+1})}{d(f_t)} > 0$, $d_{t+1}(f_t)$ is an increasing function.

(3)$\phi = 1-\frac{1}{R_0}$, $\frac{d(d_{t+1})}{d(f_t)} = 0$, $d_{t+1}(f_t)$ is a constant function.

Proof of Lemma 1.

When the vaccine effectiveness always satisfies $\phi > 1-\frac{1}{R_0}$, for $f_t < \alpha$, $d_{t+1}(f_t) = 1-\beta$. Then $d_{t+1}(1-\beta) = \alpha$. And the coverage would never beyond $[\alpha, 1-\beta]$ Besides, when $1-\beta > f_{cf}$, $r(1-\beta) = H(1-\beta) = P(1-\beta) = r(f_{cf}) = H(f_{cf}) = P(f_{cf}) = 0$. At this time, $d_{t+1}(1-\beta) = d_{t+1}(f_{cf})$. It contradicts Proposition 2 (1).

Proof of Lemma 2.

For $\phi > 1-\frac{1}{R_0}$, $d_{t+1}(f_0)$ is a decreasing function in $[\alpha, 1-\beta]$. There are $d_{t+1}(\alpha)-\alpha \geq 0$ and $d_{t+1}(1-\beta)-(1-\beta) \leq 0$. So there must exist an f_0 satisfying $d_{t+1}(f_0) = f_0$.

Proof of Proposition 3.

First, setting n_t^* and calculating n_{t+1}^*,

$\frac{\partial\pi(n_t,n_{t+1})}{\partial n_{t+1}} = w\int_0^{\frac{Nd_{t+1}}{n_{t+1}}} ydZ_y(y) - c$; $\frac{\partial\pi^2(n_t,n_{t+1})}{\partial n_{t+1}^2} = -w\frac{(Nd_{t+1})^2}{(n_{t+1})^3}z(\frac{Nd_{t+1}}{n_{t+1}}) < 0$.

Then n_{t+1}^* satisfies $\frac{\partial\pi(n_t,n_{t+1})}{\partial n_{t+1}} = 0$. Then calculating n_t^*, $\frac{\partial\pi(n_t,n_{t+1})}{\partial n_t} = w\int_0^{\frac{Nd_t}{n_t}} ydZ_y(y) - c + \frac{\partial\pi(n_t,n_{t+1})}{\partial n_{t+1}^*}\frac{dn_{t+1}^*}{dn_t}$; $\frac{\partial\pi^2(n_t,n_{t+1})}{\partial n_t^2} = -w\frac{(Nd_t)^2}{(n_t)^3}z(\frac{Nd_t}{n_t}) + (\frac{\partial\pi^2(n_t,n_{t+1})}{\partial(n_{t+1}^*)^2}(\frac{dn_{t+1}^*}{dn_t})^2 + \frac{\partial\pi(n_t,n_{t+1})}{\partial n_{t+1}^*}\frac{d^2n_{t+1}^*}{d(n_t)^2}$. Because n_{t+1}^* satisfies $\frac{\partial\pi(n_t,n_{t+1})}{\partial n_{t+1}} = 0$, $\frac{\partial\pi^2(n_t,n_{t+1})}{\partial(n_{t+1}^*)^2} < 0$ and $(\frac{dn_{t+1}^*}{dn_t})^2 > 0$, then $\frac{\partial\pi^2(n_t,n_{t+1})}{\partial n_t^2} < 0$. So n_t^* satisfies $\frac{\partial\pi(n_t,n_t)}{\partial n_t} = 0$.

Proof of Proposition 4.

$\frac{dB}{df_t} = -g(J(f_t))[\frac{w(1-\alpha-\beta)(\phi+\frac{1}{R_0}-1)}{(1-\eta(1-\phi))(1-\phi f_t-\frac{1}{R_0})^2}] + k_t$;

$\frac{d^2B}{df_t^2} = -g(J(f_t))[\frac{2w(1-\alpha-\beta)\phi(\phi+\frac{1}{R_0}-1)}{(1-\eta(1-\phi))(1-\phi f_t-\frac{1}{R_0})^3}] - g'(J(f_t))\frac{w(1-\alpha-\beta)(\phi+\frac{1}{R_0}-1)}{(1-\eta(1-\phi))(1-\phi f_t-\frac{1}{R_0})^2}$. (1) $\phi > 1-\frac{1}{R_0}$. When $\frac{2\phi g(J(f_t))}{1-\phi f_t-\frac{1}{R_0}} + g'(J(f_t)) \geq 0$, where $J(f_t) = \frac{w(1-f_t)}{r(f_t)-H(f_t)}$, $\frac{d^2B}{df_t^2} \leq 0$. It is easy to prove that $\frac{2\phi g(J(f_t))}{1-\phi f_t-\frac{1}{R_0}} + g'(J(f_t)) \geq 0$ when f_t is not higher than $1-\beta$ for normal distribution and that $\frac{2\phi g(J(f_t))}{1-\phi f_t-\frac{1}{R_0}} + g'(J(f_t)) > 0$ for uniform distribution. Then f_{2P}^{M*} satisfies $\frac{dB}{df_t} = 0$. (2) $\phi < 1-\frac{1}{R_0}$. $k_t > 0$, $\frac{dB}{df_t} > 0$, $f_{2P}^{M*} = 1-\beta$.

Proof of Lemma 3.

$\frac{dTC_{1P}}{df_t} = m[L\frac{dH(f_t)}{df_t}\int_{u_t}^1 vdG(v) - LH(f_t)u_tg(u_t)\frac{du_t}{df_t} + L\frac{dP(f_t)}{df_t}\int_0^{u_t} vdG(v) + LP(f_t)u_tg(u_t)\frac{du_t}{df_t}] + (m-1)W + \frac{C}{K_0}$;

$\frac{d^2TC_{1P}}{f_t^2} = m[2Lu_tg(u_t)\frac{u_t}{f_t}\frac{d(P(f_t)-H(f_t))}{df_t} + L(P(f_t)-H(f_t))g(u_t)(\frac{du_t}{df_t})^2 + L\frac{d^2P(f_t)}{df_t^2}\int_0^{u_t} vdG(v)] < mLg(u_t)\frac{du_t}{df_t}\frac{d(u_t(P(f_t)-H(f_t)))}{df_t}$ (1) $\phi > 1-\frac{1}{R_0}$, $\frac{d(P(f_t)-H(f_t))}{df_t} < 0$, $\frac{d^2P(f_t)}{df_t^2} > 0$, $\frac{d^2TC_t}{df_t^2} > 0$, so TC_t is a convex function. (2) $\phi < 1-\frac{1}{R_0}$, $\frac{d(P(f_t)-H(f_t))}{df_t} > 0$, $\frac{d^2P(f_t)}{df_t^2} < 0$. Because u_t and f_t are for the same period, $Lu_t(P(f_t)-H(f_t)) = W$ and $\frac{dLu_t(P(f_t)-H(f_t))}{df_t} = 0$. Then TC_t is a concave function.

Proof of Proposition 6.

$\frac{dTC_{2P}}{df_t} = \frac{dTC_{1P}(f_t)}{df_t} + \frac{dTC_{1P}(f_{t+1})}{df_{t+1}}\frac{df_{t+1}}{df_t}$; set $\frac{dTC_{1P}(f_t)}{df_{II}} = 0$ and $f_V = d_{t+1}^{-1}(f_{II})$. (1) Regarding Propositions 4 and 5, we get $\frac{df_{t+1}}{df_t} < 0$, $\frac{d^2f_{t+1}}{df_t^2} < 0$, $\frac{d^2TC_{1P}(f_t)}{df_t^2} > 0$, $\frac{d^2TC_{1P}(f_{t+1})}{df_{t+1}^2} > 0$. When $f_t \leq min\{f_{II}, f_V\}$, $\frac{dTC_{1P}(f_t)}{df_t} < 0$ and $\frac{dTC_{1P}(f_{t+1})}{df_{t+1}} > 0$. Then $\frac{dTC_{2P}}{df_t} < 0$. When $f_t > max\{f_{II}, f_V\}$, $\frac{dTC_{1P}(f_t)}{df_t} > 0$ and $\frac{dTC_{1P}(f_{t+1})}{df_{t+1}} < 0$. Then $\frac{dTC_{2P}}{df_t} > 0$. So f_{2P}^{G*}

is in the interval $[min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$. (2) Regarding Propositions 4 and 5, we get $\frac{df_{t+1}}{df_t} > 0$, $\frac{d^2TC_{1P}(f_t)}{df_t^2} < 0$, $\frac{d^2TC_{1P}(f_{t+1})}{df_{t+1}^2} < 0$. When $f_t \leq min\{f_{II}, f_V\}$, $\frac{dTC_{1P}(f_t)}{df_t} > 0$ and $\frac{dTC_{1P}(f_{t+1})}{df_{t+1}} > 0$. Then $\frac{dTC_{2P}}{df_t} > 0$. When $f_t > max\{f_{II}, f_V\}$, $\frac{dTC_{1P}(f_t)}{df_t} < 0$ and $\frac{dTC_{1P}(f_{t+1})}{df_{t+1}} < 0$. Then $\frac{dTC_{2P}}{df_t} < 0$. So f_{2P}^{G*} is 0, 1, or in the interval $[min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$.

Proof of Proposition 7.

a. It means $d_{t+2} < f_t$ for $f_t > f_0$ or $d_{t+2} > f_t$ for $f_t < f_0$. Then it is easy to get the proposition. b. It means $d_{t+2} > f_t$ for $f_t > f_0$ or $d_{t+2} < f_t$ for $f_t < f_0$. c. It means $d_{t+2} = f_t$. d. It means $d_{t+1} < f_t$. e. It means $d_{t+1} > f_t$. f. It means $d_{t+1} = f_t$.

Proof of Proposition 8.

$\frac{d\pi_{MP}}{df_t} = \frac{1}{e}[\frac{d(f_t+f_{t+1})}{df_t} + \frac{d(f_{t+2}+f_{t+3})}{df_{t+2}}\frac{df_{t+2}}{f_{t+1}}\frac{df_{t+1}}{f_t} + ...]$ (1) Regarding Proposition 4, we get $\frac{d^2B}{df_t^2} \leq 0$. Besides, $\frac{df_{t+2}}{df_{t+1}} \leq 0$ and $\frac{df_{t+1}}{df_t} \leq 0$. a. We first consider the situation of $f_{t+2} < f_t$ for $f_t > f_0$ or $f_{t+2} > f_t$ for $f_t < f_0$. If $f_0 > f_{VI}$, for all $f_t > f_{VI}$, we will have $f_{t+2} > f_{VI}$, $f_{t+4} > f_{VI}$... Referring to Proposition 4, we can get $f_{MP}^{M*} < f_{VI}$. If $f_0 < f_{VI}$, for all $f_t < f_{VI}$, we will have $f_{t+2} < f_{VI}$, $f_{t+4} < f_{VI}$... Referring to Proposition 4, we can get $f_{MP}^{M*} > f_{VI}$. b. The situation of $f_{t+2} > f_t$ for $f_t > f_0$ or $f_{t+2} < f_t$ for $f_t < f_0$ is as follows. For all $f_t > max\{f_0, f_{VI}\}$, we have $f_{t+2} > max\{f_0, f_{VI}\}$, $f_{t+4} > max\{f_0, f_{VI}\}$... For all $f_t < min\{f_0, f_{VI}\}$, we have $f_{t+2} < min\{f_0, f_{VI}\}$, $f_{t+4} < min\{f_0, f_{VI}\}$... Referring to Proposition 4, we can get f_{MP}^{M*} in the interval $[f_0, f_{VI}]$.

(2) When $\phi < 1 - \frac{1}{R_0}$, $\frac{dB}{df_t} > 0$ and $\frac{df_{t+1}}{f_t} \leq 0$ for all f_t. So $\frac{d\pi_{MP}}{df_t} \geq 0$.

Proof of Proposition 9.

$\frac{dTC_{MP}(f_t)}{df_t} = \frac{dTC_{2P}(f_t)}{df_t} + \frac{dTC_{2P}(f_{t+2})}{df_{t+2}}\frac{df_{t+2}}{df_t} + ... + \frac{dTC_{2P}(f_{m-1})}{df_{m-1}}\frac{df_{m-1}}{df_t}$. (1) Regarding Proposition 1 (1), it is easy to prove that $\frac{df_{t+2}}{df_t} \geq 0, ...\frac{df_{m-1}}{df_t} \geq 0$. In case a, the coverage will gradually be close to f_0. Regarding Proposition 6, f_{2P}^{G*} is in the interval $[min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$. If $max\{f_{II}, f_V\} < f_0$, for $f_t \geq f_0$ we have $\frac{dTC_{2P}(f_t)}{df_t} \geq 0, \frac{dTC_{2P}(f_{t+2})}{df_{t+2}} \geq 0, ..., \frac{dTC_{2P}(f_{m-1})}{df_{m-1}} \geq 0$. Then we get $f_{MP}^{G*} < f_0$. And it is easy to prove that $f_{MP}^{G*} \leq f_0$ when $min\{f_{II}, f_V\} \geq f_0$. In case b, the coverage is gradually away from f_0. So f_{MP}^{G*} is also in the interval $[min\{f_{II}, f_V\}, max\{f_{II}, f_V\}]$.

Appendix B

Proofs for Chapter 3

SIR model.

The SIR model, which is a basic and simple infectious disease model, origins from Kermack and McKendrick (1927). For influenza and other diseases, the dynamics of which is always much faster than the dynamics of birth and death, we always use the SIR model without vital dynamics to formulate its dynamics (Hethcote 2000). From Bauch and Earn (2004), Mamani et al. (2012) and Chick et al. (2008), we get the estimation of $r(f)$ ((3.3) and $p(f)$: $p(f) = \eta(1-\phi)r(f)$). Mamani et al. (2012) find that for the special case where $\phi = 0.9$, when $\mu = 3.3$, the figure is quite close to reality. Therefore, we simulate our propositions with the above approximation.

Proof for Lemma 5.

Weycker et al. (2005) estimate the average direct infection cost as 96 dollars. CDC (2009) shows that the wholesale prices of vaccine are in the range of six to 14 dollars. So we assume $w = 0.1$ in Figure 3.3. Actually, it does not matter which value we set to w, because we just want to find the relationship between ξ and f. We can get the first derivative of ξ from (3.6) as follows: $\frac{w}{(1+\xi)^2} = (r'(f) - p'(f))\frac{df}{d\xi}$. Obviously, the left-hand side of this equation is larger than or equal to zero. From the assumption (III) in Section 3.1, it is easy to get $(r'(f) - p'(f)) \leq 0$. So we can get $\frac{df}{d\xi} \leq 0$, thereby establishing this lemma.

Proof for Lemma 6.

$P(f) - p(f) = \frac{r(f)-p(f)}{1-f}$. Referring (3.3) and $p(f)$ (i.e., $p(f) = \eta(1-\phi)r(f)$), we can get $\frac{d^2(P(f)-p(f))}{df^2} = \frac{1}{(1-f)^4}[(2-2f)(1-\eta(1-\phi))(-\frac{1}{R_0})]$. Because $0 \leq f \leq 1$, $(1-f)^4$ and $(2-2f)$ will be positive. $p(f) = \eta(1-\phi)r(f)$ and $p(f) \leq r(f)$, so $1-\eta(1-\phi) \geq 0$. And $-\frac{1}{R_0} < 0$. Then $P(f) - p(f)$ is a convex function of f.

Proof for Propositions 10 and 11.

In Figure 3.4, $\phi = 0.9$, $\lambda = 0.1$ (Mamani et al. 2012), and $R_0 = 2$ (Wikipedia, Basic reproduction number, 1918). From (3.12), we can easily get: $\frac{dSC}{df} = t - (\lambda + \frac{1+\xi}{2(1+2\xi)})\phi - \frac{\xi(1+\xi)}{1+2\xi}\phi\mu(1-\phi) + \frac{(2\xi-1)(\xi+1)}{2(1+2\xi)}\frac{d(f(r(f)-p(f))}{df}$, and $\frac{d^2SC}{df^2} = \frac{(2\xi-1)(\xi+1)}{2(1+2\xi)}\frac{d^2(f(r(f)-p(f))}{df^2}$. Through the assumption that $f(r(f)-p(f))$ is a concave function, the total social cost is a convex function when $\xi < 0.5$, and a concave function when $\xi > 0.5$. When $\xi = 0.5$, $min\ SC = tf + (\lambda + \frac{1+\xi}{2(1+2\xi)})r(f) + \frac{\xi(1+\xi)}{1+2\xi}p(f)$, $\frac{dSC}{df} = t - (\lambda + \frac{1+\xi}{2(1+2\xi)})\phi - \frac{\xi(1+\xi)}{1+2\xi}\phi\mu(1-\phi) = t - (\lambda + \frac{3}{8})\phi - \frac{3}{8}\phi\mu(1-\phi)$. It is easy to get f^*:

$$f^* = \begin{cases} 0 & \text{if } t > (\lambda + \frac{3}{8})\phi + \frac{3}{8}\phi\mu(1-\phi), \\ min\{\frac{R_0-1}{\phi R_0}, 1\} & \text{if } t \leqslant (\lambda + \frac{3}{8})\phi + \frac{3}{8}\phi\mu(1-\phi). \end{cases}$$

This situation is the same as the case where $\xi > 0.5$. Then we can get Propositions 10 and 11. We also consider the special case where the vaccine is perfect. At this time, $\phi = 1$ and $p(f) = 0$. Then we can get: When $\xi < 0.5$,

$$f^* = \begin{cases} 0 & \text{if } t > n_0, \\ \frac{(2\xi+1)(c+h-\lambda)}{(\xi+1)(2\xi-1)} + \frac{\xi-1}{2\xi-1} - \frac{1}{2R_0} & \text{if } m_0 \leq t \leq n_0, \\ \frac{R_0-1}{R_0} & \text{otherwise}, \end{cases}$$

where

$$m_0 = \lambda + \frac{1+\xi}{2(1+2\xi)}(2\xi + \frac{1-2\xi}{R_0}),$$

$$n_0 = \lambda + \frac{1+\xi}{2(1+2\xi)}(2 - 2\xi + \frac{2\xi-1}{R_0}).$$

When $\xi \geq 0.5$

$$f^* = \begin{cases} 0 & \text{if } t > \widetilde{c_0}, \\ \frac{R_0-1}{R_0} & \text{if } t \leqslant \widetilde{c_0}, \end{cases}$$

where $\widetilde{t_0}$ is the solution of $S(0) = S(\frac{R_0-1}{\phi R_0})$.

Proof for Proposition 12.

Sometimes the optimal coverage under a higher coefficient of regret suggests a higher coverage (e.g., in area I of Figure 3.4), and sometimes a lower coverage (e.g., in area II of Figure 3.4). For $\phi = 0.8$ or $\phi = 1$, these two kinds of situations also exist at the same time. When ϕ decreases to a small value, there might be only the situation where the optimal coverage under a higher coefficient of regret suggests a higher coverage. But when ϕ is an uncertain value in [0,1], the optimal coverage under a higher coefficient of regret is possible to suggest a higher coverage, and also a lower coverage.

Proof for Lemma 8.

From (3.14), it is easy to get: $\frac{d\pi_i}{df_i} = -t + \frac{1+\xi}{1+2\xi}(r(f) - p(f)) + \frac{f}{n}\frac{1+\xi}{1+2\xi}(r'(f) - p'(f))$. Because $f(r(f)-p(f))$ is a concave function, (3.14) is also a concave function. When $f = 0$, $\frac{d\pi_i}{df_i} = \frac{1+\xi}{1+2\xi}(r(0)-p(0))-t$. When $f = \bar{F}$, $\frac{d\pi_i}{df_i} = -t+\frac{\bar{F}}{n}\frac{1+\xi}{1+2\xi}(r'(f)-p'(f))$. This derivative is always less than zero, because $r(f) - p(f)$ is a non-increasing function.

Proof for Proposition 13.

Figure 3.6 shows the relationship between customers' demand and manufacturers' supply. From Lemma 7, we get $w = \frac{1+\xi_d}{1+2\xi_d}(r(f_d) - p(f_d))$. Since $\frac{1+\xi_d}{1+2\xi_d} > 0$ and $r'(f) - p'(f) < 0$, (3.6) will be a non-increasing function of w. Similarly, it's easy to prove that the supply function in Lemma 8 is also a non-increasing function of t.

Proof for Proposition 14.

Referring to Lemma 8, when $t = 0$, we have $1 - \frac{1}{R_0} + (\frac{1}{n} - \phi)f_n = 0$. It is easy to find that as n increases, the value of f_n when $t = 0$ increases. When n achieves $+\infty$, $f_n = f_d = f^*$. Referring to Lemmas 7 and 8, when w achieves $\frac{1+\xi}{1+2\xi}(r(0) - p(0))$, f begins to be equal to 0 and when $t = \frac{1+\xi}{1+2\xi}(r(0) - p(0))$, f begins to be equal to 0. And it is easy to know $\frac{1+\xi}{1+2\xi}$ is a decreasing function for ξ between 0 and 1. Therefore, we can get Proposition 14.

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