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ABSTRACT

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This paper analyses the profit maximising capacity choice of a monopolistic vaccine producer facing the uncertain event of a pandemic in a homogenous population of forward-looking individuals. For any capacity level the monopolist solves the intertemporal price discrimination problem within the dynamic setting generated by the standard mathematical epidemiological model of infectious diseases. The monopolist thus bases its investment decision on the expected profits from the optimal price path given the infection dynamics. It is shown that the monopolist will always choose to invest in a lower production capacity than the social planner. Through numerical simulation it is demonstrated how the loss to society of having a monopoly producer decreases with the speed of infection transmission. Moreover, it is illustrated how the relationship between the monopolist's optimal vaccination rate and its time discount rate crucially depends on the cost of production capacity.

JEL Classification: D42, D62, H10, I18 and L10
Keywords: vaccines

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On the optimal production capacity for influenza vaccine*

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February 2008

Abstract

This paper analyses the profit maximising capacity choice of a monopolistic vaccine producer facing the uncertain event of a pandemic in a homogenous population of forward-looking individuals. For any capacity level the monopolist solves the intertemporal price discrimination problem within the dynamic setting generated by the standard mathematical epidemiological model of infectious diseases. The monopolist thus bases its investment decision on the expected profits from the optimal price path given the infection dynamics. It is shown that the monopolist will always choose to invest in a lower production capacity than the social planner. Through numerical simulation it is demonstrated how the loss to society of having a monopoly producer decreases with the speed of infection transmission. Moreover, it is illustrated how the relationship between the monopolist's optimal vaccination rate and its time discount rate crucially depends on the cost of production capacity.

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1 Introduction

It is well established that the world production capacity for influenza vaccine is far below the needs in case of a pandemic. Not only is there no production capacity for poorer countries, but the short run supply of influenza vaccine is below the population in the developed world. This has been noted by the WHO (2006), which urges countries to increase the production capacity for vaccine.[1]

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[1]The estimated vaccination capacity depends on the type of infection. WHO (2006) e.g. estimates that only 250 million individuals would recieve a full vaccination course in one year in the event of a pandemic in the H5N1 avian influenza given the production yield of such a vaccine, and under the assumption that two doses are needed to induce protective immunity.

Consistent with the presence of important scale economies, global vaccine production is dominated by a few large producers. The production involves a substantial fixed cost in terms of research and development and thereafter a low marginal production cost (DiMasi et al. 1991). Firms also tend to operate in different geographical markets. There are, for instance, two manufacturers supplying the U.S. market[2], and in several European countries, there is only one supplier. In this paper we show that monopolistic vaccine production may be harmful to society not only because of high prices but also because of a too low production capacity.

The paper analyses the profit maximizing capacity choice of a monopolistic vaccine producer facing the uncertain event of a pandemic in a homogenous population of forward-looking individuals. A production capacity level corresponds to a rate of vaccination, which in turn determines the dynamics of the pandemic. For any given capacity it is optimal for the monopolist to let the price of vaccine vary over time in response to the infection dynamics. Hence, the model generates dynamic price discrimination. An increase in capacity is associated with higher sales volumes, but also with higher costs and lower prices per dose because of a decrease in the willingness to pay for vaccine due to a lower risk of becoming infected. When choosing the optimal capacity level the producer will thus have to trade off these effects.

It is shown that the producer's optimal capacity choice is always below the socially optimal one. The fundamental reason for this is that higher vaccine production depresses the equilibrium price of vaccine because of the positive externality associated with reduced disease transmission by vaccinated individuals. This dissuades the monopolist from increasing the capacity, while it affects the social planner's capacity choice positively. The paper also explores other comparative static properties of the model through numerical simulations. It is shown how the discrepancy between the monopolistic and the socially optimal capacity choices becomes smaller if the speed of transmission of an infection is increased. The effect of an increase in the monopolist's discount rate is ambiguous; it crucially depends on the cost of production capacity.

Conceptually this paper belongs to the recent strand of literature where mathematical epidemiology and economics have been merged.[3] It studies a pandemic which is transmitted from person to person, where the probability of getting infected is proportional to the number of infected people in the population and the same for all susceptible individuals. Hence, the case of a vector-borne disease is not considered, as in Gersovitz and Hammer (2005). More specifically, the focus is on the transition of a fast-spreading pandemic, allowing us to make some specific assumptions.

We assume that there are no births, no deaths, and no recovery.[4] In the absence of a vaccine,

[2]These are Chiron Corporation and Aventis Pasteur.

[3]See, for example, Kremer (1996), Philipson (1996), Francis (1997), Geoffard and Philipson (1997), Philipson (2000) and Gersovitz and Hammer (2004 and 2005).

[4]Francis (1997) makes these specific assumptions to demonstrate that it is possible that the competitive

the number of infected individuals will therefore increase monotonously. Hence, the benefits of immunity through vaccination and thus the willingness to pay for vaccine will increase over time. In our setting the benefit of vaccination is always larger than the marginal cost for producing a unit of vaccine. Geoffard and Philipson (1997) and Philipson (2000) demonstrate, in a model where infected individuals can die or recover, that it is hard to eradicate diseases in steady-state, because the benefit of vaccination will be exceeded by its costs once the infection rate is sufficiently small. This is, however, not an issue under our specific assumptions.

Within our dynamic framework households are assumed to perfectly anticipate how the pandemic will evolve, like in Gersovitz and Hammer (2004). The impact on individual behavior has previously been incorporated in Kramer (1996), where, however, behavior is determined only by present conditions. Here both present and future conditions are perfectly anticipated, thus providing individuals with the correct incentives for purchasing vaccine.[5]

Kremer and Snyder (2003) make the point that producers may prefer to develop drug treatments instead of vaccines, since a vaccine reduces or stops the spread of a disease, and it is not possible to extract rents for a vaccine from the yet unborn. In contrast, a drug does not prevent the spread of the disease, which means that each coming generation will require the drug. However, this mechanism, may be less relevant in the case of a fast spreading new influenza or pandemic. The technology for producing vaccine is known and can be employed as soon as a pandemic virus strain is identified, whereas a drug against a particular virus would take considerable time to develop.[6] No therapeutic or preventive efforts are therefore considered; the only way to reduce the risk of getting infected is through vaccination and hence, there are no trade-offs between treatment and vaccination.

Intertemporal price discrimination arises in our setting, although it is assumed that the population is entirely homogenous. However, the model could easily be extended such that account is taken of income heterogeneity among individuals, whereby the individual with the highest willingness to pay for vaccine would be targeted in every instant. Thus price discrimination of the type examined by Kessing and Nuscheler (2006) in a static setting would arise, such that the timing of vaccination would be inversely correlated with income.

The following section presents the model. In section 3 and 4 supply decisions of a monopolist and a social planner are examined, respectively, while in section 5 optimal outcomes under these

outcome may coincide with the socially optimal outcome, i.e. that no externality arises. Gersovitz (2003) explains how this result is driven by the underlying assumptions in Francis (1997).

[5] Kramer (1996) focuses on attitude towards risk in the context of HIV, where individuals do not know their status (infected or not), whereas the present paper concentrates on the individual decision to vaccinate or not when individuals have perfect knowledge about their status. The rational fatalism phenomenon is therefore not an issue.

[6] There are, of course, drugs as oseltamivir (tamiflu) which strengthens the immunal response to virus in general. Still the effectiveness of such a drug against a new pandemic is not known beforehand.

two regimes are compared. In Section 6 numerical simulations of the model are presented, and finally section 7 concludes.

2 The Model

The standard model of epidemics first presented in Kermac and McKendrick (1927) contains three categories of individuals: susceptible (S), infected (I) and resistant (R) individuals. The latter category includes individuals that have been infected, but have recovered and become resistant. We apply a simplified version of the Kermac and McKendrick (1927) model, where, for tractability, it is assumed that the birth and mortality rates are zero. Setting these rates to zero may be justified by the fact that pandemics usually occur for only a relatively short time period (the pandemics of the previous century encircled the globe in 6 to 9 months). Furthermore, it will be assumed that once an individual has been infected, this individual will live forever, but never recover, i.e. the mortality and recovery rates of pandemics are both zero. This implies that the number of infected individuals will be larger and hence, the pandemic will spread faster.

In the absence of a vaccination program the dynamics of the epidemic solely depend on the transmission parameter β, which is related to epidemiological, environmental and social factors. The pandemic dynamics are determined by the following sets of equations.

$$\dot{I} = \beta SI, \tag{1}$$

$$\dot{S} = -\beta SI, \tag{2}$$

$$\dot{R} = 0. \tag{3}$$

The rate of infection is given by the individual hazard rate βI and the number of susceptibles S. For simplicity it will be assumed that I, S and R represent shares of the population, i.e. $I_t + S_t + R_t = 1$ at any point in time t.

In the presence of a vaccination program equations (1)-(3) need to be modified. It is, however, necessary to make some assumptions on the conditions for the implementation of the vaccination program. First, it will be assumed that the government will initiate the execution of the vaccine program whenever the outbreak of a pandemic is established, which is here taken to mean that the number of infected individuals reaches a certain predetermined threshold level I^*.[7] Second, it will be assumed that whenever a vaccination program has been initiated by the government, there is a technical production time lag before sales and distribution of the vaccine actually starts. Let τ be the time lag between the decision to start a vaccination program and the start of vaccination.

[7] Alternatively, it could be assumed that the execution of a vaccination program is initiated when a pandemic starts spreading in e.g. East Asia. In this case it would be necessary to make assumptions about how a pandemic is transmitted geographically.

At time 0 the number of infected is I^*, i.e. $I_0 = I^*$, and the government decides that a vaccine has to be produced. Before production actually starts, at time τ, the epidemic evolves according to equations (1) and (2). Assuming that no one is resistant at the time of outbreak, i.e. $R_0 = 0$, it is the case that $S_t = 1 - I_t$ for $t \in [0, \tau]$ and hence, (1) can be expressed as follows for $t \in [0, \tau]$:

$$\dot{I} = \beta(1 - I)I = \beta I - \beta I^2, \qquad I_0 = I^*. \tag{1'}$$

The solutions for S and I when $t \in [0, \tau]$ are thus given by

$$I_t = \frac{I^*}{I^* + (1 - I^*)e^{-\beta t}}, \tag{4}$$

$$S_t = \frac{(1 - I^*)e^{-\beta t}}{I^* + (1 - I^*)e^{-\beta t}}. \tag{5}$$

It is easy to see that $\frac{\partial I_t}{\partial \beta} > 0$ and $\frac{\partial S_t}{\partial \beta} < 0$; a more severe epidemic will increase the share of infected individuals at any point in time. Moreover, everyone will be infected asymptotically ($I_t \to 1$, $S_t \to 0$) in the absence of a vaccine.

Once production and distribution of vaccine starts, the dynamics of the epidemic are influenced by the vaccination rate u.[8] Vaccination will continue until time $T = T(u)$, when there are no more susceptible individuals.[9] The pandemic dynamics for $t \in [\tau, T]$ are determined by the following set of equations:

$$\dot{I} = \beta SI \tag{6}$$

$$\dot{S} = -\beta SI - u \tag{7}$$

$$\dot{R} = u, \tag{8}$$

with starting values I_τ and S_τ, determined by (4) and (5), and $R_\tau = 0$. The solutions for

[8] We implicitly assume that production, once initiated, is always at full capacity. Theoretically a monopolist could produce at a rate lower than full capacity so as to extract higher profits. We do not consider this possibility. It could be argued that production at a rate lower than full capacity would be politically impossible in case of a pandemic. It could also be assumed that the monopolist makes a legally binding commitment to produce at a certain vaccination rate u.

[9] Here we implicitly assume that the willingness to pay for vaccine is always larger then the marginal cost of producing one dose of vaccine. A sufficient condition for this to be the case is provided in section 3.2.

$t \in [\tau, T]$ are given by

$$I_t = \frac{\sqrt{\beta u} e^{\beta(t-\tau)-\frac{1}{2}\beta u(t-\tau)^2}}{\left(\begin{array}{l} \sqrt{2}\beta e^{\frac{\beta}{2u}} \int_\tau^{\tau+\sqrt{\frac{\beta}{2u}}[u(t-\tau)-1]} e^{-(t'-\tau)^2} dt' \\ \quad +\sqrt{2}\beta e^{\frac{\beta}{2u}} \int_0^{\sqrt{\frac{\beta}{2u}}} e^{-t'^2} dt' + \frac{\sqrt{\beta u}}{I^*}[I^* + (1-I^*)e^{-\beta\tau}] \end{array} \right)} \tag{9}$$

$$\begin{aligned} S_t &= 1 - u(t-\tau) \\ &\quad - \frac{\sqrt{\beta u} e^{\beta(t-\tau)-\frac{1}{2}\beta u(t-\tau)^2}}{\left(\begin{array}{l} \sqrt{2}\beta e^{\frac{\beta}{2u}} \int_\tau^{\tau+\sqrt{\frac{\beta}{2u}}[u(t-\tau)-1]} e^{-(t'-\tau)^2} dt' \\ \quad +\sqrt{2}\beta e^{\frac{\beta}{2u}} \int_0^{\sqrt{\frac{\beta}{2u}}} e^{-t'^2} dt' + \frac{\sqrt{\beta u}}{I^*}[I^* + (1-I^*)e^{-\beta\tau}] \end{array} \right)} \end{aligned} \tag{10}$$

$$R_t = u(t-\tau). \tag{11}$$

It is easy to see that I and R strictly increase, while S strictly decreases in t. The point in time when the vaccination program ends (T) is obtained as the solution to $S_t = 0$. Once the vaccination program has ended, the shares of susceptible, infected and resistant individuals remain constant. Hence, for $t \geq T$ we have

$$I_t = 1 - u(T-\tau) \tag{12}$$

$$S_t = 0 \tag{13}$$

$$R_t = u(T-\tau). \tag{14}$$

The following lemma addresses the effect of an increase in the vaccination rate u.

Lemma 1 *An increase in u will lead to a decrease in I_t, a decrease in the duration of the vaccination program $T - \tau$ and an increase in the share of vaccinated individuals $u(T-\tau)$.*

Proof. An increase in u will increase R and decrease S. This is the first-order effect of an increase in u. A decrease in S implies a decrease in $\frac{\dot{I}}{I}$ and hence, a decrease in I. Could I fall so much that S would actually increase? Assuming this to be the case would imply that $\frac{\dot{I}}{I}$ increases, thus making S smaller, in contradiction to the assumption. Hence, it can be ruled out that S will increase due to an increase in u. Since S decreases in response to an increase in u, the duration of the vaccination program $T - \tau$ must fall. Because I decreases, it follows immediately that the share of vaccinated individuals $R_T = u(T-\tau)$ must increase. ■

In our model susceptibles become infected or, in case a vaccine is available, resistant. Whereas in the absence of vaccination everyone will become infected asymptotically, the possibility to vaccinate against the disease will bring about a steady state with only infected and resistant individual in finite time. Since there are no deaths, the disease will actually not be eradicated.[10]

[10] Gersovitz (2003) points out that under the specific conditions in Francis (1997) eradication of the disease is

3 Supply by a Monopolist

3.1 The Optimal Pricing Scheme

The population is assumed to be homogenous in the sense that all individuals have the same wage rate w and the same preferences. Vaccine is supplied at the price determined by the monopolist. It will be assumed that no further costs (utility losses) are associated with vaccination.

Given the homogeneity of the population, the optimal pricing scheme will be such that individuals are indifferent to the point in time for purchasing the vaccine. The monopolist will thus set the price at time T so that the last susceptible individual is indifferent between purchasing the vaccine and not (i.e. never) buying it. Prices at time $t < T$ will be set such that individuals will be indifferent between purchasing it instantly and postponing buying vaccine at time T, implying that individuals at all times will be indifferent between purchasing the vaccine and never ever buying it.

Let δ be the common discount rate of all individuals. Consider a susceptible individual at time t. If this individual becomes ill at time $t' > t$, the discounted value of this individual's earnings before being infected is given by

$$\int_t^{t'} we^{-\delta(t''-t)}dt'' = \frac{w}{\delta}(1 - e^{-\delta(t'-t)}). \tag{15}$$

For any $t \in [\tau, T]$ the optimal price p_t of the vaccine makes individuals indifferent between purchasing the vaccine instantly and never ever buying it. Hence, the optimal price p_t has to satisfy the following equation:

$$\begin{aligned}&\frac{w}{\delta} - p_t \\ &= \int_t^{\infty} \lambda_{t'} e^{-\int_t^{t'} \lambda_{t''}dt''} \frac{w}{\delta}(1 - e^{-\delta(t'-t)})dt' + [1 - \int_t^{\infty} \lambda_{t'} e^{-\int_t^{t'} \lambda_{t''}dt''}dt']\frac{w}{\delta},\end{aligned} \tag{16}$$

where $\lambda_t \equiv \beta I_t$ is the force of the infection. The left-hand side of (16) represents the value of purchasing the vaccine. The first term on the right-hand side represents the aggregated expected discounted income of an individual becoming infected at some point in the future. The conditional probability of becoming sick at time $t' > t$ in the future is given by $\lambda_{t'} e^{-\int_t^{t'} \lambda_{t''}dt''}$, and the expected discounted value of incomes when becoming sick at time t' is given by (15). The second term represents the expected discounted value of never ever becoming sick, where the probability of never ever getting sick is given by $1 - \int_t^{\infty} \lambda_{t'} e^{-\int_t^{t'} \lambda_{t''}dt''}dt'$ (which may or may not be equal to zero).

optimal, both for individuals and for the government. If, however, births are introduced, or if infected individuals can recover and become susceptible again, this will be the case only if the cost of infection is infinite or the cost of immunization is zero.

Rearranging (16) gives us the optimal price for $t \in [\tau, T]$:

$$p_t = \frac{w}{\delta} \int_t^\infty \lambda_{t'} e^{-\int_t^{t'} \lambda_{t''} dt''} e^{-\delta(t'-t)} dt'. \tag{17}$$

By rearranging expression (17) an alternative expression for p_t is obtained.

$$\begin{aligned} p_t &= \frac{w}{\delta} \{ \int_t^\infty (\lambda_{t'} + \delta) e^{-\int_t^{t'} (\lambda_{t''} + \delta) dt''} dt' - \int_t^\infty \delta e^{-\int_t^{t'} (\lambda_{t''} + \delta) dt''} dt' \} \\ &= \frac{w}{\delta} \{ 1 - \delta \int_t^\infty e^{-\int_t^{t'} (\lambda_{t''} + \delta) dt''} dt' \}. \end{aligned} \tag{18}$$

From the assumption of no mortality and no recovery it immediately follows that the share of infected individuals, and thus the hazard rate, increases over time, thereby increasing (18). The following lemma formally demonstrates that p_t increases in t.

Lemma 2 *The optimal price for vaccine increases over time: $\dot{p_t} \geq 0$ ($\dot{p_t} > 0$ for $t < T$ and $\dot{p_t} = 0$ for $t = T$). However, the discounted value of the price for vaccine decreses over time: $\frac{d(p_t e^{-\delta t})}{dt} < 0$.*

Proof. The time derivative of (17) is given by

$$\begin{aligned} \dot{p_t} &= \frac{w}{\delta} [(\lambda_t + \delta) \int_t^\infty \lambda_{t'} e^{-\int_t^{t'} \lambda_{t''} dt''} e^{-\delta(t'-t)} dt' - \lambda_t] \\ &= (\lambda_t + \delta) p_t - \frac{\lambda_t w}{\delta} = \delta p_t + \lambda_t (p_t - \frac{w}{\delta}). \end{aligned}$$

Substituting p_t with expression (17) and $p_t - \frac{w}{\delta}$ with expression (18) yields

$$\dot{p_t} = w \int_t^\infty \lambda_{t'} e^{-\int_t^{t'} \lambda_{t''} dt''} e^{-\delta(t'-t)} dt' - \lambda_t w \int_t^\infty e^{-\int_t^{t'} (\lambda_{t''} + \delta) dt''} dt'.$$

Since $\lambda_{t'} \geq \lambda_t$ for $t' \geq t$ when $t < T$ and $\lambda_{t'} = \lambda_T$ for $t' \geq T$, it immediately follows that $\dot{p_t} > 0$ for $t < T$ and $\dot{p_t} = 0$ for $t = T$.

The time derivative of $p_t e^{-\delta t}$ is given by

$$\begin{aligned} \frac{d(p_t e^{-\delta t})}{dt} &= \dot{p_t} e^{-\delta t} - \delta p_t e^{-\delta t} = [(\lambda_t + \delta) p_t - \frac{\lambda_t w}{\delta}] e^{-\delta t} - \delta p_t e^{-\delta t} \\ &= \lambda_t (p_t - \frac{w}{\delta}) e^{-\delta t} < 0. \end{aligned}$$

■

A monopoly supplier of vaccine will choose a vaccination rate such that the optimal pricing scheme it induces maximizes expected profits. The impact of an increase in u on p_t is assessed in the following lemma.

Lemma 3 *An increase in u makes p_t smaller for any t.*

Proof. By inspection of (18) it is easy to see that because an increase in u makes I_t lower (see lemma 1) and hence λ_t smaller for any $t > \tau$, p_t will become unambiguously smaller. ■

Increasing the vaccination rate implies that more vaccine will be sold (see lemma 1), but at a lower price. The monopoly supplier thus faces a trade-off between more vaccine being sold on the one hand, and higher costs and lower prices on the other hand.

3.2 Profits

At the time when the investment in the capacity for producing vaccine is made, the exact point in time when there will be an outbreak of the pandemic is unknown. Assume that the probability for when an outbreak occurs is governed by a Poisson process. In this case the probability of an outbreak having occurred at time t in the future is given by $1 - e^{-\alpha t}$, and the density function of the distribution for when an outbreak will occur is given by $\alpha e^{-\alpha t}$.

The parameter α indicates how imminent an outbreak is. A higher α implies a higher likelihood for an outbreak occurring in finite time; letting α go to zero, the likelihood of an outbreak in finite time becomes zero, and letting α go to infinity, the likelihood of an imminent outbreak becomes one. It is easy to see that $\frac{1}{\alpha}$ is the expected value for when an outbreak will occur.

The monopolist invests in a capacity for producing vaccines at rate u, thereby incurring the cost $C(u)$, where $C'(u) > 0$. Let $P(u)$ be the discounted value of the flow of producer surplus once an outbreak has occurred, and let $\rho \leq \delta$ be the discount rate of the monopolist. The expected profit Π is thus given by

$$\begin{aligned}\Pi(u) &= -C(u) + \int_0^\infty \alpha e^{-\alpha t} P(u) e^{-\rho t} dt \\ &= -C(u) + \frac{\alpha}{\alpha + \rho} P(u). \end{aligned} \tag{19}$$

It is easy to see that for $\alpha = 0$, it will not be worthwhile to invest in any capacity at all, because the expected value of producer surplus is zero due to the fact that no outbreak is expected in finite time. A higher α, implying a higher likelihood of an imminent outbreak occurring, naturally increases the expected value of the gains from investing in vaccination capacity.

The profit maximization problem of the supplier generates the following optimality condition:

$$C'(u) = \frac{\alpha}{\alpha + \rho} P'(u), \qquad \Pi''(u) < 0, \qquad \Pi(u) \geq 0. \tag{20}$$

Let c be the constant marginal cost of producing one unit of vaccine. The producer surplus is thus given by

$$P(u) = \int_{\tau}^{T(u)} u[p_t(u) - c]e^{-\rho t}dt. \tag{21}$$

Here, we will assume that the marginal cost of producing vaccine is sufficiently small to always make it profitable to produce.[11] As noted above, p_t increases over time. Hence, we will assume that $p_\tau(u) \geq c$ always holds. Since $p'_\tau(u) < 0$ (see lemma 3), a sufficient condition for $p_t \geq c$ to hold for any t is given by $\lim_{u\to\infty} p_\tau(u) \geq c$, i.e.

$$c \leq \frac{\lambda_\tau}{\lambda_\tau + \delta}\frac{w}{\delta}.$$

For any given c the above condition is satisfied for sufficiently high levels of β (note that $\frac{\lambda_\tau}{\lambda_\tau+\delta}$ increases unambiguously in β) and/or sufficiently low values of δ.

4 Supply by the Government

The objective of the government is to minimize losses due to a pandemic, i.e. to maximize aggregate income net of costs for vaccine production. The government incurs a cost by building up a capacity for vaccine production, here assumed to be equal to the investment costs $C(u)$ of a monopolist supplier. Furthermore costs will arise when there has been an outbreak of the disease and when production of vaccine starts. Let $G(u)$ be the discounted value of the government surplus at the time of outbreak. Because producer surplus is smaller than the willingness to pay for vaccine, which in turn is smaller than aggregate income, it follows that $G(u) > P(u)$ for any u. At the time of investment the government's welfare function W is given by

$$\begin{aligned} W(u) &= -C(u) + \int_0^\infty \alpha e^{-\alpha t} G(u) e^{-\delta t} dt \\ &= -C(u) + \frac{\alpha}{\alpha+\delta} G(u). \end{aligned}$$

The optimization problem of the government generates the following first-order condition:

$$C'(u) = \frac{\alpha}{\alpha+\delta} G'(u), \qquad W''(u) < 0, \qquad W(u) \geq 0. \tag{22}$$

Since all individuals earn the same wage w, the discounted value of the government surplus at the time of outbreak is given by

$$G(u) = \int_0^\tau w S_t e^{-\delta t} dt + \int_\tau^\infty \{w[1 - I_t(u)]e^{-\delta t} dt - \int_\tau^T cue^{-\delta t} dt. \tag{23}$$

[11] If $p_\tau(u) < c$, the monopoly supplier will have an incentive to postpone the production of vaccine. This outcome has been examined in Forslid (2006) who applies a similar model.

The first term, reflecting the flow of incomes during the phase prior to the vaccination program, is unaffected by u. The second term, consisting of the income generated by uninfected people, unambiguously increases in u, because a higher u implies a lower share of infected individuals for all $t > \tau$ (see lemma 1). The last term, which measures the variable costs of producing vaccine, also increases in u. Hence, there are two opposing effects of increasing the vaccination rate, in addition to the negative effect of increasing the capacity at the vaccine production plant. Which effect dominates is addressed in the following section.

5 Optimal Outcomes

The following lemma assesses the impact of an increase in u on government and producer surpluses.

Lemma 4 *Given that the marginal cost of producing vaccine is sufficiently small, $G(u)$ increases monotonically in u (i.e. $G'(u) > 0$). The effect of a higher u on $P(u)$ is always smaller than the impact on $G(u)$ (i.e. $P'(u) < G'(u)$) and can even be negative.*

Proof. Consider the last individual receiving vaccine at time T. If this individual is not given any vaccine, the marginal cost c is saved. However, this individual will incur an individual loss corresponding to the willingness to pay for vaccine (the difference between the flow of income of being vaccinated and the expected flow of income of not being vaccinated). The net loss of abstaining from vaccinating this individual is thus given by $(p_T - c)e^{-\delta T}$, which by assumption is strictly positive. Hence, $G'(u) > 0$.

For a monopoly supplier not selling the last dose of vaccine implies a marginal loss $(p_T - c)e^{-\rho T}$. However, there is also a second, opposite effect from not vaccinating the last individual. Since this individual will become infected in finite time, the disounted value of future hazard rates will increase marginally and hence, the price of vaccine will increase marginally for all $t \in [\tau, T]$, thereby marginally increasing the producer surplus. To understand why this is the case, consider the willingness to pay of the second last individual purchasing vaccine if the last individual abstains from getting vaccinated. Because the hazard rate will become slightly larger in the future, the second last individual will be willing to pay slightly more for its dose of vaccine. Naturally, the same applies to all individuals purchasing vaccine. Hence, not vaccinating the last individual will increase revenues from all other individuals. This second effect has to be weighed against the loss of selling one dose of vaccine less. Therefore the total effect of abstaining from vaccinating this individual on producer surplus can be either positive or negative, and it will always be strictly larger than the negative impact on government surplus. Hence, $P'(u) < G'(u)$. ■

Thus an increase in u will always have a more positive impact on the government surplus than on the producer surplus. It follows immediately that, if there exists a strictly positive

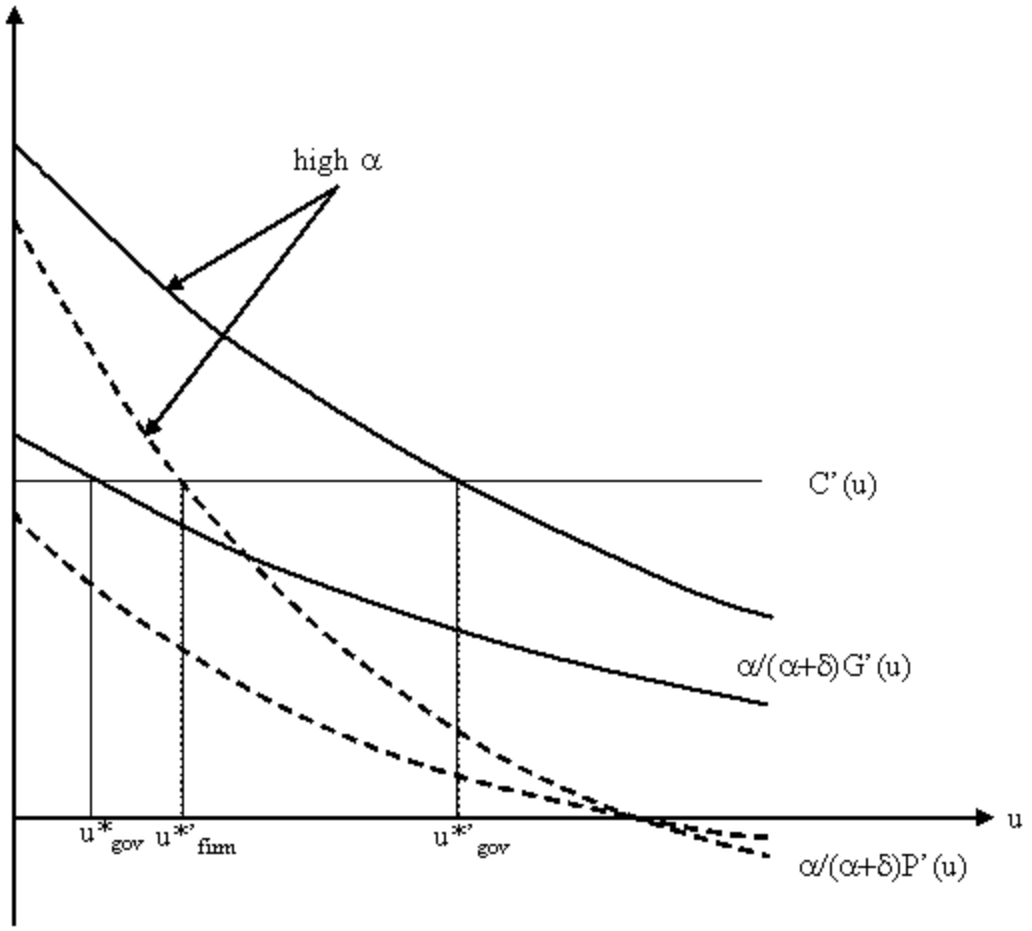

Figure 1: Optimal vaccination rates

solution to (20), then the solution to (22) must be strictly larger. This result is summarized in the following proposition.

Proposition 5 *The government will never opt for a lower vaccination rate than a monopoly supplier. In particular, whenever there exists a strictly positive optimal solution for the monopolist, the government will choose a strictly higher vaccination rate.*

The following figure sketches how the optimal solutions for the government and a monopoly supplier depend on the degree of imminence of a pandemic outbreak, measured by α.[12] For simplicity $C'(u)$ is assumed to be constant and is represented by the dashed line, while $\frac{\alpha}{\alpha+\delta}G'(u)$ is represented by bold lines and $\frac{\alpha}{\alpha+\rho}P'(u)$ is represented by thin lines. Optimal solutions, if they exist, are given by the intersections between $C'(u)$ and $\frac{\alpha}{\alpha+\delta}G'(u)$, and between $C'(u)$ and $\frac{\alpha}{\alpha+\delta}P'(u)$, respectively.

[12] Note that α does not impact on $P(u)$ and $G(u)$.

First, consider the case when α is very low (not shown in the figure), such that $\frac{\alpha}{\alpha+\delta}G'(u) \leq C'(u)$ for all $u \geq 0$. From proposition 1 it immediately follows that $\frac{\alpha}{\alpha+\rho}P'(u) \leq C'(u)$ for all $u \geq 0$. In this case neither the government nor a monopoly supplier will provide any vaccination capacity, the underlying reason being that the likelihood of an outbreak occurring soon is too low to justify the cost of setting up a vaccine factory.

Next, we let α increase such that there exist some $u > 0$ for which $\frac{\alpha}{\alpha+\delta}G'(u) > C'(u)$, but $\frac{\alpha}{\alpha+\rho}P'(u) \leq C'(u)$ for all $u \geq 0$. In this case the government will choose to provide some vaccination capacity $u^* > 0$, given that all the conditions in (22) are satisfied, while a monopolist will not provide any vaccination capacity. Hence, the outbreak of a pandemic is not imminent enough for a private supplier to build a vaccine factory, whereas the social planner expects a net benefit of providing at least some capacity. This case is illustrated by the lower curves in Figure 1, and the vaccination rate u^*_{gov}.

If α is increased further, such that there exist some $u > 0$ for which $\frac{\alpha}{\alpha+\rho}P'(u) > C'(u)$, then both the government and a monopoly supplier will provide some vaccination capacity, given that all the conditions in (22) and (20) are satisfied.[13] The imminence of a pandemic outbreak is now large enough to justify an investment by a monopolist, but the monopolist's capacity will always be smaller than the optimal capacity of the government, as illustrated by $u^{*'}_{gov}$ and $u^{*'}_{firm}$ in Figure 1.

6 Simulations

In order to more fully explore the model we now turn to numerical simulations.

6.1 The supply cost of vaccine

We parametrize the cost of production capacity for vaccine according to

$$C = a + bu^{\gamma}, \quad \gamma > 0. \tag{24}$$

a represents the cost associated with setting up vaccine production, and b the cost associated with capacity i.e. with the vaccination rate u. The function may be concave or convex in u. It is possible that scale economies in production tend to make $\gamma < 1$, however, it is also possible that capacity constraints when it comes to the physical vaccination (lack of nurses etc.) implies that $\gamma > 1$. We will assume that $\gamma = 1$ in the base case simulation. Finally, there is also the constant marginal cost of producing one unit of vaccine c.

[13] Note that $\frac{\alpha}{\alpha+\rho}P(u) - C(u) \geq 0$ implies $\frac{\alpha}{\alpha+\delta}G(u) - C(u) > 0$, because $G(u) > P(u)$ and $\rho \geq \delta$.

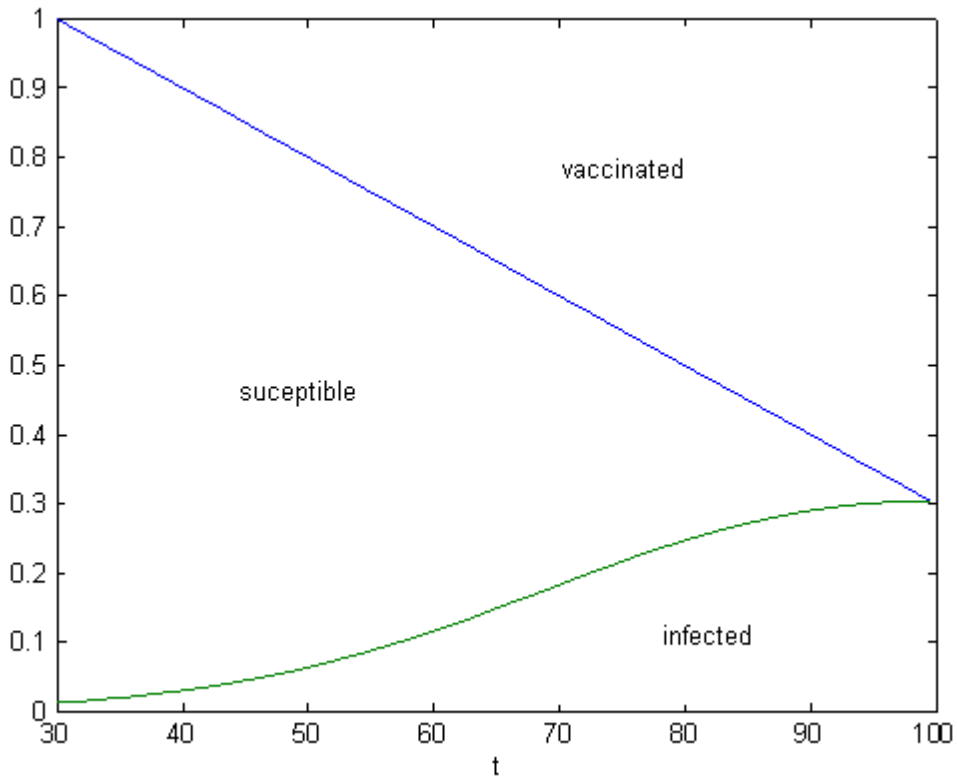

Figure 2: Infection Dynamics

6.2 A base case simulation

The base case simulation is calibrated to Swedish data. The following parameters values are used in the base case simulation: $\beta = 0.09, \rho = \delta = 0.0001, \gamma = 1, I_0 = 0.001, \tau = 30, w = 5.79 \cdot 10^5, a = 10^6, b = 10^{13}, c = 1$. The base case value for β implies that 90 percent of the population would be infected in 100 days if there where no medication or vaccine to stop the spread of the infection. The discount rates correspond to a 4 percent annual discount rate. The wage is set as the wage share of the Swedish 2006 GDP per day. It is quite difficult to assign a value to the parameters of the cost function a and b. We will in the base case assign high values to these parameters implying that it would cost 10 billion USD to vaccinate the entire Swedish population in 100 days. This inflicts a distinct curvature to the planners problem and rules out that the planner chooses very high vaccination rates. We will, however, also discuss cases where costs are much lower. Figure 2 shows the epidemic dynamics in the base case for $u = 0.01$,[14] and the corresponding profit maximizing price path is plotted in Figure 3.

As shown above, the planner would always chose a higher rate of vaccination u than the

[14]The system is first solved backwards for different guesses of T. After T is found p_T is calculated, and the entire system incuding profits and government surplus is again run from T to τ.

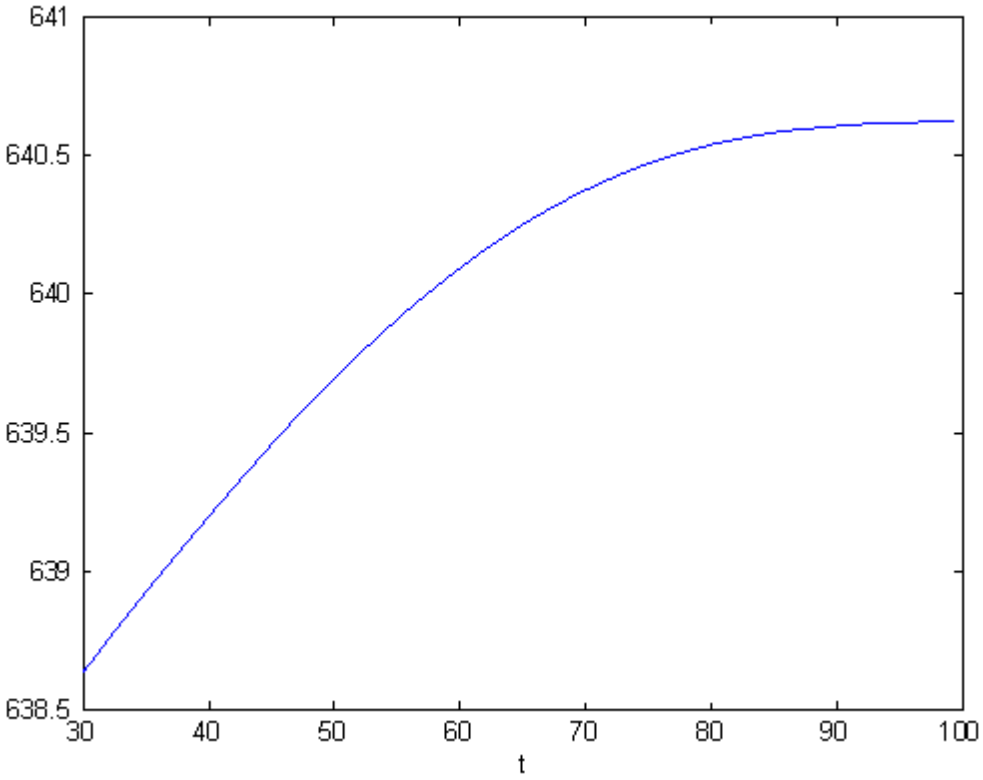

Figure 3: The price path

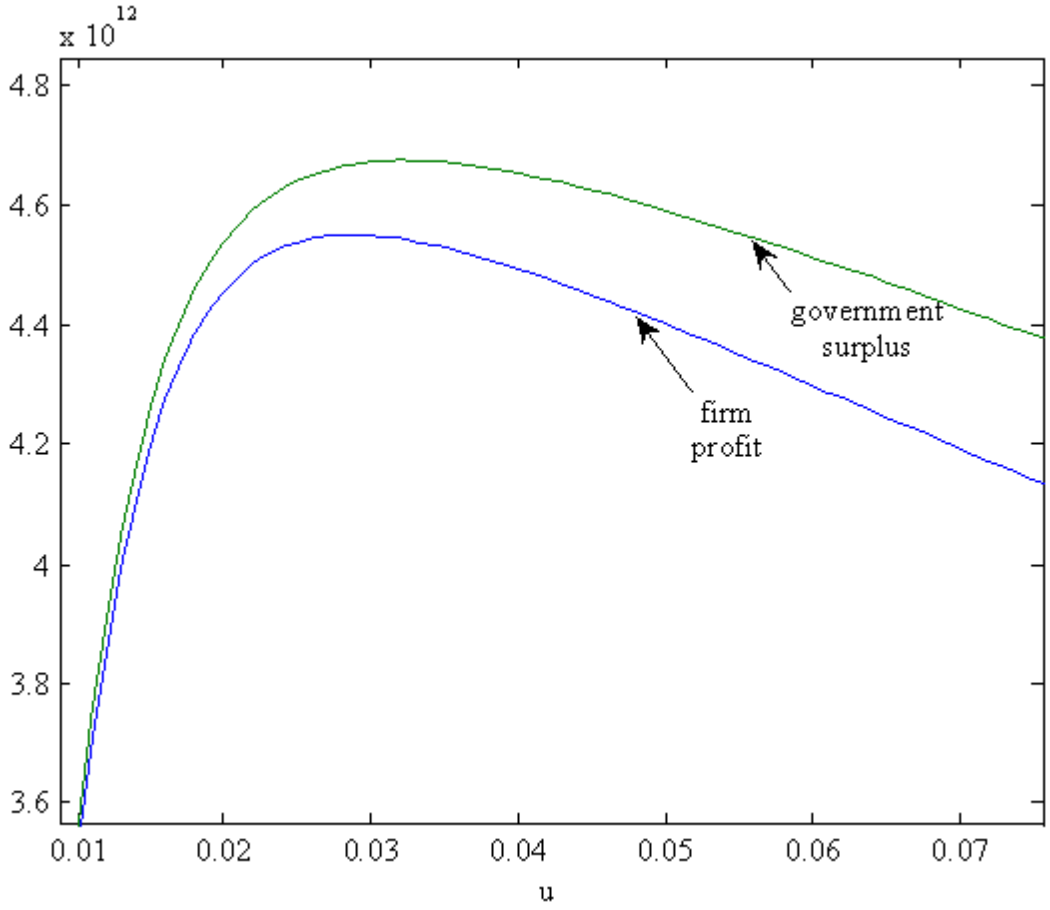

Figure 4: Government surplus and firm profit

monopolist. This is illustrated in the base case in Figure 4, which plots the discounted profit of the monopolist and the discounted surplus of the planner for a range of $u's$. The peak of the planners/governments curve will always lie to the right of monopolists.

We now turn to simulating how the optimal vaccination rate for the firms and the planner is affected by changes in a number of key parameters of the model, for which analytical results are hard to find. Clearly, we can not claim that our simulation results holds in general, even if they have been robust during our numerical experiments.

6.2.1 The transmission speed

The transmission parameter β determines how fast a particular infection spreads through the population. An increase in β will lead to a fall in aggregate income as more people become infected. To avoid an increasing share of infected individuals a higher rate of vaccination is needed, which implies higher costs. Thus a higher β is unambiguously negative for the planner. For the firm, the effect of a higher β is ambiguous. On the one hand it makes it possible to charge a higher price, because higher hazard rates increase the willingness to pay for vaccine.

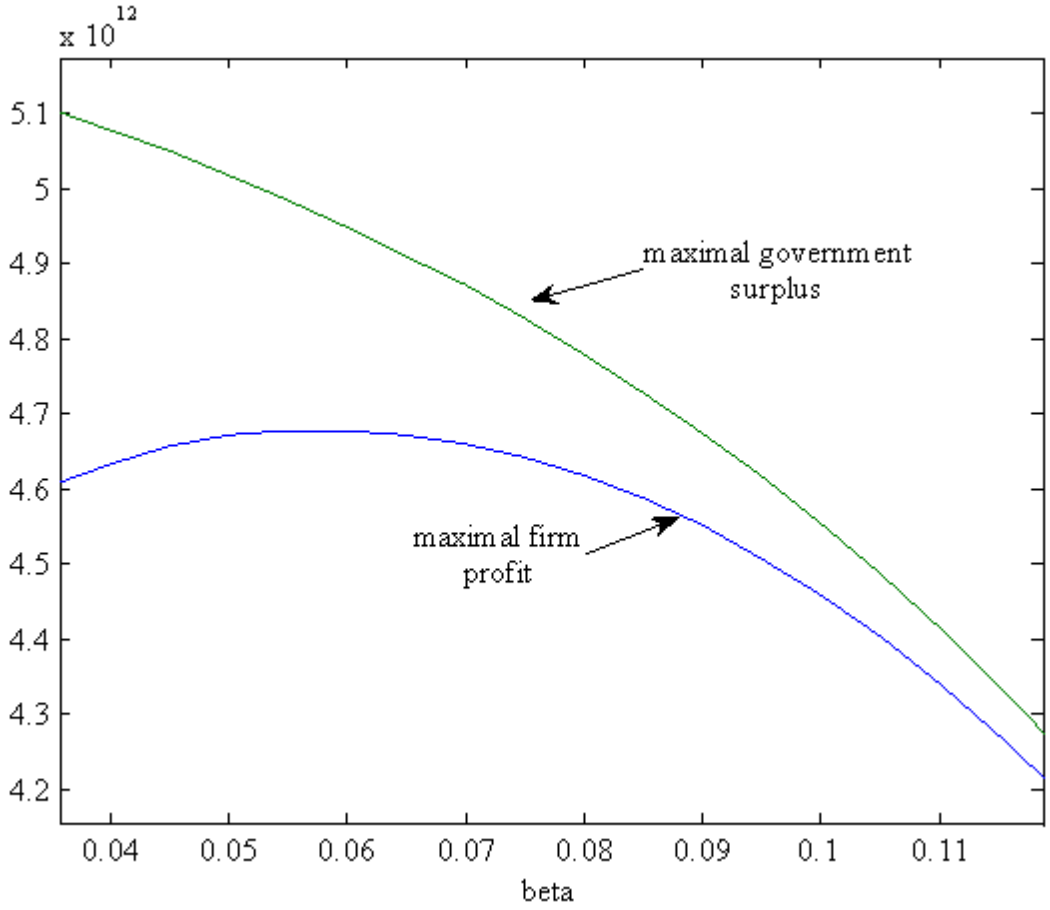

Figure 5: Profit and government surplus as β changes

On the other hand, at a constant rate of vaccination u, the firm will sell less vaccine due to the increase in the number of infected individuals. To maintain its sales the firm would have to choose a higher and more costly rate of vaccination.

Figure 5 shows a simulation of government surplus and firm profit as a function of β. The firm´s profit is humpshaped in β. The firm profit is zero for $\beta = 0$, because in this case no vaccine needs to be produced, and it goes to zero as β goes to infinity, since the whole population will already be infected at time τ. The simulations also show how a higher β always leads the firm and the planner to chose a higher rate of vaccination, u. Also the difference between the planner's and the firm's u decreases in absolute terms as β increases. As a consequence, the simulations show that the loss to society of having the firms profit maximizing u, instead of the planners vaccination rate, declines in β.

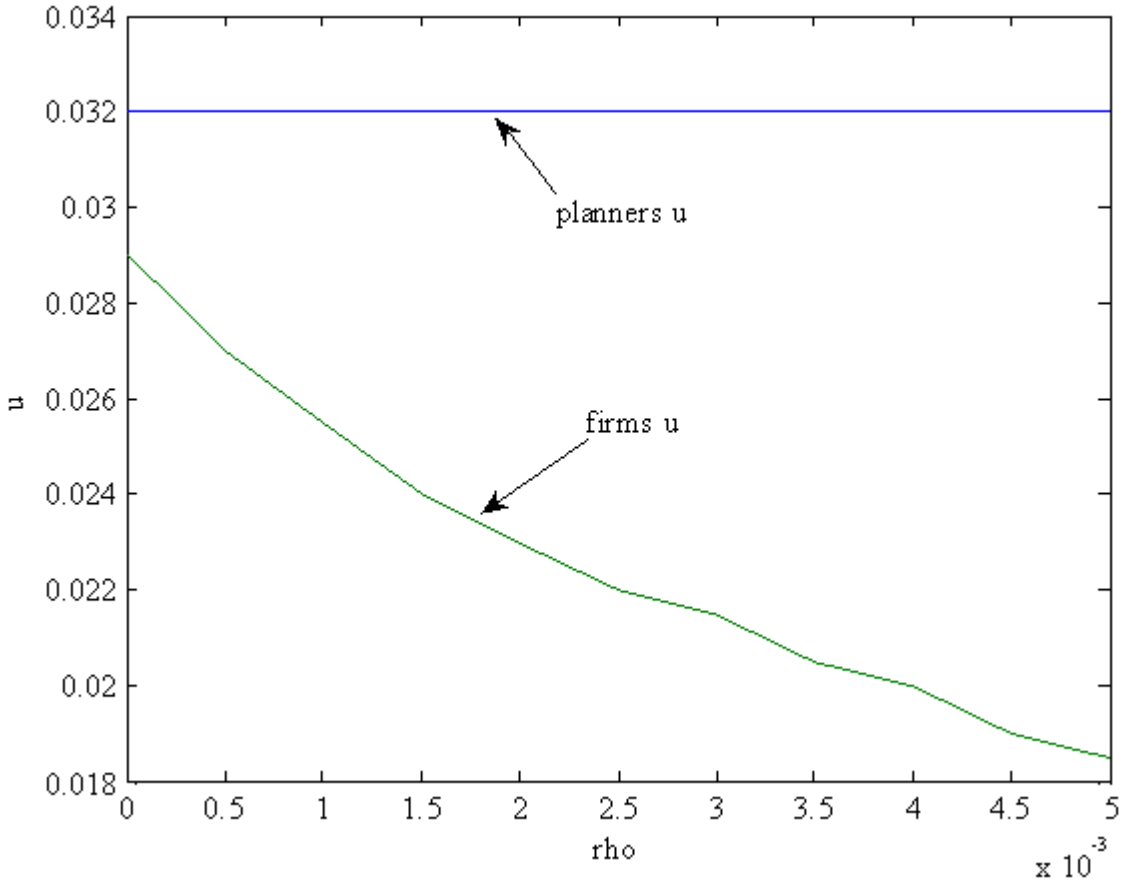

Figure 6: Optimal vaccination rates as functions of ρ when investment costs are high

6.2.2 Discounting

Consider first the case when the firm and the planner have the same time discount factor: $\rho = \delta$. Higher discounting of the future surplus generated by vaccine distribution makes capacity investments less attractive for the monopolist as well as for the planner, and for a sufficiently high discount rate neither the firm nor the planner will invest in capacity for vaccine production

A second experiment is to vary the firm discount rate ρ, while holding δ constant. One interpretation of this experiment, stepping slightly outside the model, is that we are varying the degree of competition in the vaccine market. A first set of simulation results are shown in Figure 6. The planner's optimal vaccination rate is unaffected by ρ, while the monopolist´s optimal u declines in ρ. The firm here finds it less worth to invest in production capacity as future profits are more heavily discounted.

That u declines in ρ is, however, not obvious, since higher discounting also means that the

firm prefers a more front heavy profit stream, which would imply a higher vaccination rate.[15] Consider e.g. the incentives of a producer that has free and costless access to an unlimited production capacity. The producer would chose u to maximize profits given the dynamics of the model as usual (and the planner would chose an infinite u). Higher discounting would in this case necessarily means that the firm chooses a higher u.

In Figure 7 we simulate a case where the cost parameters are based on an estimate of the investment cost for a factory for the Swedish population. A recent government report (Rekke 2006) estimates the total investment cost for a factory for the Swedish population to around 50 million USD. Abstracting from the costs of actually performing the physical vaccination, and assuming that the entire population can be vaccinated in 30 days ($u = 1/30$), and with $a = 10^6$, gives $b = 1.47 * 10^8$. Clearly these parameters values imply much lower costs than in the base case above. As shown in the figure, firm vaccination rates now increase in ρ.

The cost to society of having a monopolist vaccine producer instead of the planner decreases in ρ when investment costs are not too high, but increases in ρ when the investment costs for production capacity is above some threshold. Interpreting ρ as a proxy for competition, it is therefore not obvious that competition policy, aiming at reducing the market power of the monopolist, would increase overall welfare. However, when calibrating the model to the estimated cost for production capacity *by* using Swedish data, investments costs seem far below the threshold where increased competition would harm society.

7 Conclusions

This paper analyses the investment incentives of a monopolist vaccine producer facing the uncertain event of a pandemic. The producer chooses optimally capacity for a rate of vaccination taking the optimal price path, given by the dynamics of the infection, into account. The producer, thus, solves it's dynamic price discrimination problem, when making it's investment decision. Consumers are likewise forward looking, and base their demand for vaccine on the expected path of the hazard of being infected.

It is shown analytically that a planner would always choose a higher vaccination rate than the monopolist, whenever there exists a positive optimal solution for the monopolist. Moreover, for some parameter values it may be the case that a monopolist chooses a zero vaccination rate, while a planner would opt for at least some vaccination capacity.

The model is thereafter explored through numerical simulations. First, we consider the effect of the rate of transmission of an infection. While the planner's utility decreases monotonically in the speed of transmission, the firm's profit displays a hump-shaped pattern. An infection

[15] See e.g. Forslid (2006), that illustrates how a monopolist vaccine producer, that has sunk the production cost, will start selling the vaccine at an earlier date when discounting increases.

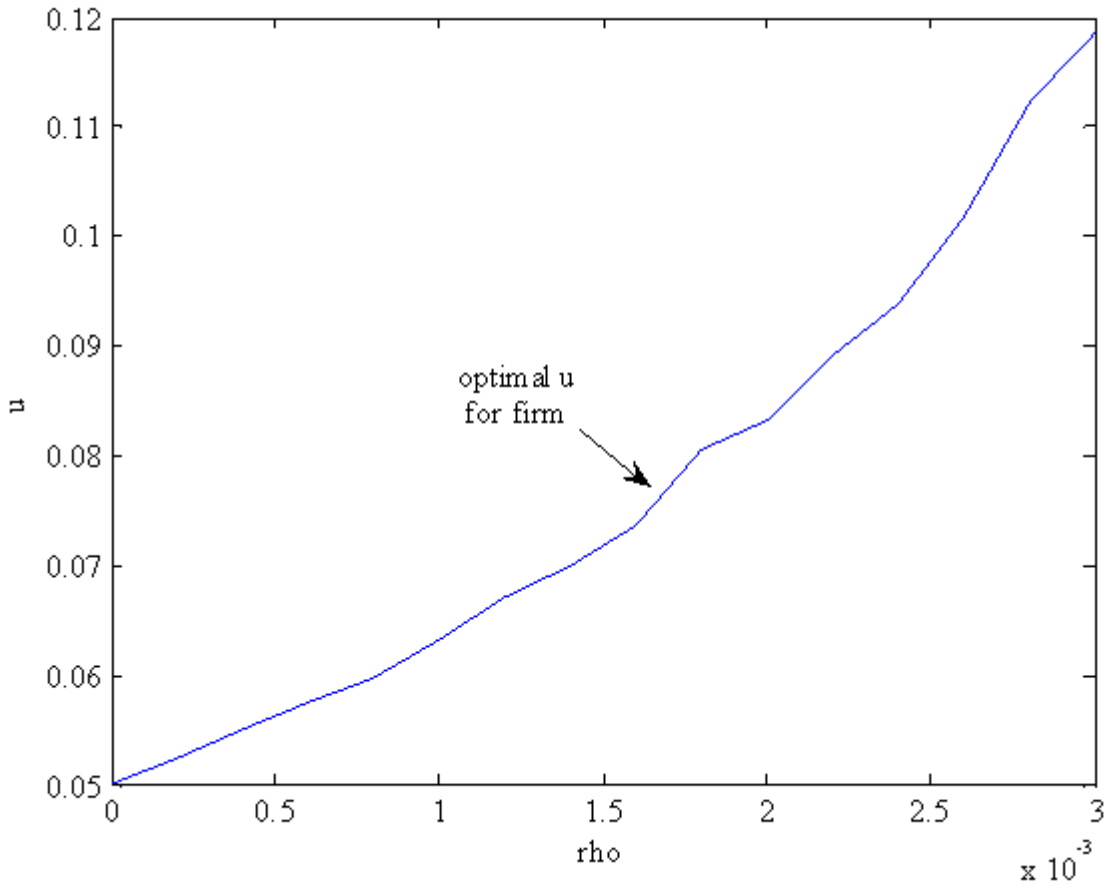

Figure 7: Optimal vaccination rate for the monopolist as a funtion of ρ when investment costs are low

that is transmitted slowly generates high hazard rates of being infected very far away in the future. These hazard rates matter relatively little for consumers' willingnesses to pay for vaccine, since consumers discount time. The producer is consequently not able to charge a very high price. In the opposite case of a very rapidly spreading infection, the producer has a very short time to sell vaccine before all susceptibles are infected. This requires a high and costly rate of vaccination, which again depresses profits. The monopolists profit is, therefore, maximized for an intermediate infection transmission rate. As a result, even though society is always worse off with an infection transmitting fast, our simulations show that the societal loss of having a monopolist producer instead of the planner is decreasing in the transmission parameter.

Second, we illustrate that the effect of the firm's discount rate, which could be viewed as a proxy for the degree of competition, is ambiguous. Firms will decrease capacity investments when their discount rate increases, if the investment costs for production capacity are high. The opposite holds, when investment costs are sufficiently low. For intuition, consider the incentives of the monopolist producer *ex ante* and *ex post* the investment. Clearly, *ex post*, the producer will want to move its revenues closer in time as the discount rate increases (e.g. because of fear for the entry of competitors). This implies a higher rate of vaccination. *Ex ante*, on the contrary, a higher discount rate makes it less attractive to invest in production capacity today. When calibrating the model to Swedish data, where we have a cost estimate for production capacity, investments in production capacity is increasing strongly in the discount rate.

It may, in this context, be interesting to compare vaccine production and other drug manufacturing. The development of a new drug often entails very high fixed costs in terms of R&D as well as clinical testing. Vaccine production, on the contrary, typically involves well known technology and a much less costly test phase. Our analysis implies that it could very well be optimal to have patent protection of new drugs, at the same time as monopolies are harmful when it comes to vaccines.

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