Journal of Economic Behavior and Organization 216 (2023) 136–149

Contents lists available at ScienceDirect

Journal of Economic Behavior and Organization

journal homepage: www.elsevier.com/locate/jebo

Negative network effects and public policy in vaccine markets ☆

Rabah Amir [a,*], Zhiwei Liu [b], Jingwen Tian [a]

[a] *Department of Economics, the University of Iowa, Iowa City, IA, USA*
[b] *International School of Economics and Management, Capital University of Economics and Business, Beijing, China*

ARTICLE INFO

JEL classification:
I11
L13
D43

Keywords:
Network effects
Demand-side externalities
Health externalities

ABSTRACT

This paper provides a thorough analysis of an oligopolistic market for a vaccine, characterized by negative (demand-side) network externalities, which stem from the free-riding behavior of individuals engaged in a vaccination game. We investigate industry viability in terms of a standard natural Cournot-type learning process for network industries and show that viability tends to favor monopoly or competition among few suppliers. We confirm that market performance is highly inefficient, due to the combination of three imperfections: market power, network effects and a health externality (i.e., contagion). We investigate the extent of these imperfections. Finally, we devise a two-part government subsidy scheme for producers and consumers that may restore social efficiency in such markets.

1. Introduction

Long before the onset of the global Covid 19 pandemic, vaccines were widely recognized as the most effective ingredient for the prevention and eradication of infectious diseases. The global vaccine market was valued at $98 billion in 2021 and is expected to reach $153 billion by 2028. However, the importance of this market in the eyes of public health officials, the medical profession and pharmaceutical firms is often not matched by people's propensity to vaccinate, despite frequent vigorous promotion campaigns for vaccines. For instance, the CDC estimates that coverage among adults for the flu vaccine in the 2020–2021 flu season was just 50.2%, and 58.6% among children (Sorensen, 2023). For Covid 19 in the US, the rate is only 68% (across all ages) in spite of the convenience and free availability of the vaccine (source: New York Times).

In light of the financial and other important costs of vaccines, one reason behind these significant gaps in coverage is the perception that the larger the fraction of vaccinated people, the less useful for protection vaccines become in the eyes of the unvaccinated, and therefore the lower their willingness to incur the vaccination costs is. This free-riding conclusion emerges naturally from simple game-theoretic models of vaccination. Among others, Brito et al. (1991), Heal and Kunreuther (2005), and Sorensen (2023) develop different versions of such games, the key property of which being that people's decisions to vaccinate are strategic substitutes.[1] The common prediction of these models is that the fraction of people who choose not to vaccinate is increasing in the cost of the

☆ The authors are grateful to Filomena Garcia, Adriana Gama, Rim Lahmandi-Ayed, Natalia Lazzati and Joana Resende for helpful feedback on the contents of this paper.

* Corresponding author.
E-mail addresses: rabah-amir@uiowa.edu (R. Amir), liuzhiwei@cueb.edu.cn (Z. Liu), gin-tian@uiowa.edu (J. Tian).

[1] Nganmeni et al. (2022) offer a cooperative games perspective. Hellmann and Thiele (2022) consider voluntary testing and self-isolation (see also Gallic et al., 2022).

https://doi.org/10.1016/j.jebo.2023.10.005
Received 8 March 2023; Received in revised form 27 August 2023; Accepted 7 October 2023

vaccine. The notion that these models serve as micro-foundations for the fact that vaccine markets are characterized by negative network effects on the demand side follows naturally. While the pioneering work of Veblen (1899) brought to the fore the notion of bandwagon or positive network effects in economics long ago, negative network effects were recast as snob effects by Leibenstein (1950). The influential studies by Rohlfs (1974, 2001) and Katz and Shapiro (1985) also considered (demand-side) positive network effects only, but at the same time included the supply side for industries with such effects, in the form of perfect competition and Cournot oligopoly respectively.

Although the idea of free riding in vaccine behavior has been recognized in several studies in the literature, only Kessing and Nuscheler (2006) consider industries with negative network externalities explicitly. This study focuses on monopoly markets and heterogeneous consumers in their income levels and invokes the idea of fulfilled expectations on the network size. The purpose of the present paper is to provide a thorough theoretical investigation of vaccine markets under oligopolistic competition and negative network effects. To do so, we adopt a simple analog of the model by Katz and Shapiro (1985), with a linear inverse demand whose intercept shrinks (instead of expanding) due to negative network effects. By taking the number of firms as a parameter, we consider a symmetric Cournot model that nests monopoly and perfect competition as special cases and invoke the widely adopted solution concept of rational-expectations Cournot equilibrium (or RECE), as in Rohlfs (1974), Katz and Shapiro (1985) and Amir and Lazzati (2011). Two simple micro-economic foundations for the derivation of demand under negative network effects are also given. In such a setting, both firms and consumers are cognizant of the presence of negative network externalities and have rational and concordant expectations as to how the latter affect the equilibrium outcome.

Exploiting the convenient specification of the model with linear demand and costs, the unique RECE is easily fully characterized via closed-form solutions for all variables of interest. With some plausible extrapolation from a simple static analysis, the unique RECE of the model is shown to capture three of the main salient stylized facts that pertain to this industry, according to authoritative accounts of the evolution of these industries by Arnould and DeBrock (1996), Scherer (2007) and Danzon and Pereira (2011). These stylized facts may be summarized as follows: (i) a natural monopoly or oligopoly with few firms as a stable market structure, (ii) the emergence of such market structure following a sizable shake-out from an initial period with high levels of competition, and (iii) an unusually high and sustained increase in prices following the shake-out, along with exceptional price-cost margins for the survivors. The match between the predictions of the model with negative network effects and the key stylized facts of the vaccine industry provides a plausible alternative to Scherer's (2007) account, based mostly on the well known increasing returns to scale property of vaccine production.

In light of our results, one might conjecture that a plausible scenario of a behavioral nature to explain the (ex post) unwise decision to enter for the firms that ended up shaken out of the market is that they were unaware of, or failed to anticipate, the negative network effects inherent in such industries. In other words, these firms had entered a vaccine market in anticipation of regular imperfect competition, e.g., in the form of standard Cournot competition.

While RECE is formally a static concept, it may be viewed as a reduced form for a quasi-dynamic, Cournot-like learning process where firms keep adjusting their outputs as the expected network size changes, starting from any initial network size (see e.g., Amir and Lazzati, 2011). While this process is monotonic in the case of positive network effects, it turns out to be oscillatory in the present case. If the resulting cobweb dynamics is divergent, which happens when network effects are strong and/or there are many firms serving the market, then the process ends up at zero output, which we interpret as instability and thus non-viability for the industry (Amir and Lazzati, 2011 and Amir et al., 2021). Under mild network effects and/or few firms in the market, the cobweb dynamics converges to the stable RECE, which is then taken as the right prediction of the model. However, under strong network effects and/or high numbers of firms in the market, the cobweb dynamics is unstable, which we interpret as indicating that the RECE does not have any predictive power as a solution concept, in line with similar conclusions about unstable equilibria (whatever their type) in economics in general. We argue that this dichotomy between stable and unstable equilibrium solutions explains the natural monopoly/oligopoly final outcome, which persists despite substantial price-cost margins in vaccine industries (Scherer, 2007).

Our results point clearly to the conclusion that market performance under a RECE, fully characterized for all possible market structures, is highly inefficient. This conclusion is not surprising at all, since the underlying model reflects three market imperfections of quite distinct natures: Market power, network effects, and a health externality in the form of contagion-induced social costs. While the latter is not taken into account by the firms in the industry, it is a key factor in the social planner's objective for regulatory purposes, as well as in the emergence of network effects in the formulation of demand.[2] The health externality (in the form of a damage term to capture the contagion effect) will be added and discussed later when social welfare is considered in Section 4.

The focus in the second part of the paper is on a subsidy scheme that may restore (first-best) social efficiency in vaccine markets. We investigate the properties of a classical two-part subsidy scheme composed of a per unit production subsidy to the firms manufacturing the vaccine and a per unit subsidy to consumers purchasing the vaccine. A suitable version of such a two-part scheme is shown to be sufficient as a regulatory remedy to deliver a first-best outcome for the vaccine market. The main conclusion is that a combination of production and consumer subsidies will often be necessary to achieve the first-best outcome in a vaccine industry, in particular in case of severe epidemics (those characterized by more harmful infection for people and high contagion).

This type of double subsidy schemes are consistent with common practice in all industrialized countries, that governments subsidize vaccination against major contagious diseases and sometimes provide strong incentives for people to vaccinate, including

[2] This is partly analogous to the case of pollution, the costs of which are not taken into account by the firms whose production causes it but are always integrated into the planner's social objective function.

making it mandatory for all. The well-known rationale is that the social benefits of vaccination exceed the private benefits, precisely because of the contagion externality.

Nevertheless, since the topic of negative network effects has been mostly overlooked in formal studies even though they were discussed in the early literature, several of the present results are of more general interest, beyond the market for vaccines. The study of negative network effects is certainly a major topic worthy of further research, since these are known to arise in industries with a congestion dimension (see e.g., Ben-Elhadj et al., 2012 and Gaumont et al., 2023), at least beyond a certain level of output (e.g., parks, sports facilities, etc...) and in many luxury and/or fashion goods industries (Leibenstein, 1950).

The remainder of the paper is organized as follows. Section 2 presents an overview of the history of the vaccine industry, the model and the equilibrium concept. Section 3 deals with the stability of RECE and its basic properties. Section 4 studies first-best planning and analyzes corrective public policy in the form of subsidies. Section 5 concludes and provides some practical managerial and policy implications.

2. The model and the equilibrium concept

This section presents a summary of the history of vaccine markets in the form of key stylized facts, the standard oligopoly model with network effects along with the commonly used equilibrium concept due to Katz and Shapiro (1985), and its solution.

2.1. Salient facts about the vaccine industry

In this subsection, we collect some of the stylized facts about the vaccine industry that set it apart from a generic industry. For the sake of a short presentation, we shall ignore some important factors that are broadly associated with vaccine markets, including two-tier pricing (depending on whether government is involved as a buyer), tort liability costs, and significant supply fluctuations and interruptions.[3] This omission is not motivated by a perception that these factors are not relevant, but rather by the fact that our model and analysis focuses on other important factors.

This brief review is drawn from three specialized studies of vaccine markets, each of which provides a factual review of the features and history of these markets, along with some explanatory analysis, from Arnould and DeBrock (1996), Scherer (2007) and Danzon and Pereira (2011).

While the same firm typically supplies multiple vaccines (multi-market contact collusion), market definition typically pertains to a single vaccine, since there is no possible (medically-sanctioned) demand substitution (Arnould and DeBrock, 1996). We thus implicitly ignore (i) any cost-related links (economies of scope) due to multi-vaccine firms' operation, and (ii) any multi-market contact arguments that may be advanced to explain the scope for collusive pricing.

Arnould and DeBrock (1996) report that the vaccine industry had seen a trend towards higher concentration, with a small number (typically at most three) of domestic and foreign producers being the norm; in fact, many vaccines are supplied by single producers or monopolies, including 10 out of the 15 recommended childhood vaccines. Expanding on this key point, Scherer (2007) goes further and even talks of natural monopoly, providing a discussion of the underlying reasons, including economies of scale (with variable costs representing only 10% or less of total costs, Arnould and DeBrock, 1996). Danzon and Pereira (2011) also elaborate on this key point.

In addition, the emergence of these monopolistic market structures for vaccines followed a period with significant levels of competition, followed by high levels of market exit by multiple firms, as well as mergers and acquisitions and consolidations. While some new entry did take place over the same period, it was not nearly sufficient to get the vaccine industry back to its prior market structure. In other words, the new situation, involving either a monopolist or competition among few firms, appears to be stable. Arnould and DeBrock (1996) offer further detail and specific evidence.

The latter authors also observe that, after the above market shake-out (or major exit wave) took place, the "prices of most vaccines have increased substantially in the last few years, and some vaccine prices have increased 10- to 15-fold during the past 15 years." These authors provide some detailed evidence for this trend for specific vaccines. Scherer (2007) adds some estimated price-cost margins for vaccines as being around a staggering 56.3% on average (to be contrasted against an average of 28% for manufacturing industries as a whole, Scherer, 2007, p. 305).[4]

In the sequel, when discussing some implications of our proposed simple model, we shall refer to the general facts and trends described in the three paragraphs above as Stylized Facts #1, #2, and #3, respectively.

2.2. The model

We consider a static model of n-firm oligopolistic competition in a vaccine industry with negative network effects. These stem from individuals' correct perception that interaction with vaccinated people is safe, implying that their willingness to get vaccinated for own protection is declining with the size of the network of vaccinated people. There are n firms in the market and these firms' vaccines are assumed to be perfect substitutes and fully effective at protecting against infection, and this setting fits naturally in the

[3] See e.g., Iverson et al. (2022) for more on the role of random production timing.

[4] However, although some allege that much of the price rises were due to monopolistic behavior, others argue that 23% to 47% of the price increase is due to the federal excise tax to fund the Injury Compensation System.

case of a single network for the industry or full compatibility (Katz and Shapiro, 1985), irrespective of the number of firms serving the market.

The market inverse demand function for vaccines is (the notation $(\cdot)^+$ means $\max\{\cdot, 0\}$ throughout)

$$P(Z, S) = (a - \alpha S - bZ)^+, \tag{1}$$

where Z is the total output, and a and b are the usual positive constants for linear inverse demand. The variable S represents the expected network size and captures the number of consumers who are expected to purchase a vaccine (more on this point below) and thus the parameter $\alpha > 0$ measures the strength of the negative network effects.

Each of the n identical firms serving the market has a linear cost function $C(x) = cx$, with $0 \le c < a$. Any fixed costs of production are assumed to be sunk.

As each consumer buys at most one vaccine, S also stands for the expected number of vaccinated people.[5] The firm's profit function is then

$$\pi(x, y, S) = x[a - \alpha S - b(x + y)] - cx$$

where x is the firm's level of output, y the output of the other $(n-1)$ firms in the market (so that $Z = x + y$).

The equilibrium concept for this oligopoly model with expectations is due to Katz and Shapiro (1985) (also see Rohlfs, 1974). A rational expectations Cournot equilibrium (RECE) in this game is defined by a vector of outputs $\left(x_1^*, x_2^*, ..., x_n^*\right)$ and a scalar $S^* > 0$ that satisfy the joint conditions

1. $x_i^* \in \arg\max \left\{x(a - \alpha S - b\sum_i x_i) - cx : x \ge 0\right\}$, and
2. $S^* = \sum_i x_i^*$.

To operationalize this definition, one may think that any given (exogenous) S fixes an inverse demand $P(\cdot, S)$, for which one can find the unique (standard) n-firm Cournot equilibrium, with corresponding industry output denoted by the function $Z_n(S)$. A rational expectations Cournot equilibrium (RECE) is then equivalently defined as a fixed point of $Z_n(S)$, or

$$Z_n(S) = S$$

Thus, the equilibrium network size induces the firms to reproduce it as the Cournot equilibrium industry output. Put differently, the right inverse demand is the one that generates a Cournot equilibrium industry output corresponding to the network size associated to that demand.

This now-standard equilibrium notion, due to Katz and Shapiro (1985), presumes that firms are strategic in usual Cournot style when setting their output, but that they do so taking S as given (or behave as network-size takers).[6] As will be seen in some result interpretations below, a key aspect of this concept is that it pins down both firms' strategic decisions (output levels) and the associated "right" market size simultaneously. Put differently, the inverse demand function itself is endogenous in this concept, in contrast to other oligopoly equilibrium concepts. Some plausible justifications for this widely used concept to model network effects are provided in some detail by Katz and Shapiro (1985) and Amir and Lazzati (2011). Another observation of interest about this concept is that competing firms are rivalrous in two separate ways therein: The first is as regular Cournot players in setting outputs and the second as mutual demand-reducing actors.[7]

Finally, we assume that the firms in this industry do not take into account the social damage caused by the underlying health externality (i.e., the contagion effect) associated with an epidemic, namely the contagion feature that will be an integral part of public policy intervention in Section 4 below, where an explicit damage term will be included in the social welfare function. Nevertheless, the firms are aware of the fact that this health externality generates the network externality in the first place, and this aspect is fully taken into account by the RECE concept.

2.3. Some micro-economic foundations

This section offers two possible simple micro-economic foundations for the inverse demand function under network externalities used here. Since these two micro foundations eschew a direct role for the actual game played between consumers, we first relate the origin of the network effects for vaccines to the game faced by potential vaccine consumers.

The free-riding argument that underlies the notion of negative network externalities in the vaccine market emerges from a class of games analyzed by Heal and Kunreuther (2005), Brito et al. (1991) and Sorensen (2023), among others. With further details to be found in those studies, here we provide a summary of the salient features of the game.

[5] For vaccines with multiple doses (e.g. tetanus), the assumption is that each consumer buys one full set of vaccines. As to whether a vaccine fully or partially protects people, both may be seen to give rise to negative network externalities in the micro-foundations reviewed in the next section.

[6] An unusual aspect of this concept is that it combines Cournot equilibrium with one plausible way of determining the right demand function from a collection of such, and thus the right market size.

[7] This is in contrast to the case of positive network effects where the overall interaction is of a hybrid type since, despite their Cournot rivalry, firms are actually partners in building up a common network, thus giving rise to an interesting case of co-opetition (Brandenburg and Nalebuff, 1996).

The basic model is a symmetric binary choice game, with action 1 for "vaccinate" and action 0 for "not vaccinate", knowing that the vaccine is effective only with a given probability (as is the case for Covid 19, influenza, pneumonia and many other examples). Each agent may contract the disease from an outside source or from an infected person (with fixed probabilities for each), in which case a given cost is incurred. These studies show in related variants of this game that, for fixed parameters, there is a unique pure-strategy Nash equilibrium (up to player permutations), in which the number of people who choose to vaccinate is decreasing in the vaccine price.[8] Furthermore, for a single agent's best response problem, the incentive to vaccinate (i.e., the difference in payoffs from selecting actions 1 and 0) is decreasing in the number of vaccinated people.

This is thus a submodular game or a game of strategic substitutes. These properties clearly provide a micro-foundation for a demand function such as (1).[9] We now give two novel separate accounts for a direct origin for this demand function.

2.3.1. Option 1: quasi-linear utility for heterogeneous consumers

This approach follows along standard lines to derive a demand function from a set of heterogeneous consumers, differentiated in their stand-alone values for the vaccine but attributing the same network value to the vaccinated set in case of non-vaccination. For simplicity, we adapt for our purposes Rohlf's (1974) original model of general network effects using a simple quasi-linear (additive) utility function.

Consider a set of consumers that are uniformly distributed on the interval $[0,1]$ in terms of their intrinsic valuation (or stand-alone value) for a vaccine. Each consumer has a binary choice set: She may choose action 1 for "purchase" or action 0 for "do not purchase". The (quasi-linear) utility for the consumer located at $v \in [0,1]$ if she purchases a vaccine at price p is, with d and β being positive constants,

$$U(v,1) = d + \beta v - p.$$

The sum of the two terms d and βv forms the stand-alone value of a vaccine for this consumer. The term d may be seen as the common part of the stand-alone value to all consumers while the term βv captures the component that is agent-specific, due to various heterogeneity factors.[10] A consumer does not derive any network benefit from purchasing since the vaccination provides full protection from infection, irrespective of the number of others who vaccinate.

If this consumer does not purchase a vaccine, her outside utility is not zero (as is often assumed), since she derives indirect network benefits stemming from the reduced probability of infection due to those that have vaccinated, represented by network size S. Instead, that utility is thus, with parameter α representing the strength of network effects,

$$U(v,0) = \alpha S.$$

The consumer that is indifferent between purchasing a vaccine and not purchasing is defined by

$$U(v,1) = U(v,0) \text{ or } d + \beta v - p = \alpha S.$$

Hence, solving for v, this consumer must be located at $v = (p - d + \alpha S)/\beta$ and all the consumers to her right will choose to purchase a vaccine each. Therefore, using the pdf of the uniform distribution, the measure of these buyers is $Z = 1 - (p - d + \alpha S)/\beta$, which may be taken as the number of units sold (since every buying consumer gets one unit). Solving for p yields the inverse demand

$$P = \beta + d - \alpha S - \beta Z.$$

This is easily seen to correspond to inverse demand (1), upon identifying $\beta + d$ with a and β with b.

As a final remark, this derivation extends to an imperfect vaccine, defined as one that provides full protection with probability $q \in (0,1)$ (Sorensen, 2023). Indeed this would lead to the following plausible changes to the above (assuming expected utility as the objective) $U(v,1) = d + \beta q v - p$ and $U(v,0) = \alpha q S$. In fact, the analysis in Sorensen (2023) reflects such a feature.

2.3.2. Option 2: heterogeneous reservation prices

The second common foundation postulates a distribution of consumers according to their (heterogeneous) reservation prices, which may partly reflect their infection costs and/or incomes as in Kessing and Nuscheler (2006).[11] Consider a set of consumers that perceive the same negative network effects captured by an additive term αS (where S is the expected size of the network) and are otherwise heterogeneous in their reservation prices for a vaccine. Specifically, assume there is a mass of consumers of size $\max\{a - \alpha S, 0\}$ whose reservation prices are uniformly distributed on the interval $[0, \max\{a - \alpha S, 0\}]$, with total mass $a - \alpha S$. It follows that at a price $0 \le p \le S$, the set of consumers who purchase one unit is the mass of those consumers whose reservation price is at least p, so that using the cdf of the uniform distribution, we obtain the direct demand function as $Z = a - \alpha S - p$. Solving for p yields the inverse demand function as

$$P = a - \alpha S - Z.$$

[8] Specifically, the number of vaccinees goes from the full set when the price is very low to the empty set when the price is high enough.

[9] Interestingly, while the externality at hand is a positive one in the context of the strategic vaccine game in that every individual benefits from others' decisions to vaccinate, it becomes a negative network externality in the market context as it leads to a demand contraction through the underlying free-riding effect in vaccination.

[10] This will generally include a wide diversity of factors, some objective and others subjective, including the perceived opportunity cost of infection, the age, health state and immunity state of agents, the level of informativeness of agents about the specifics of the epidemic, psychological fear of infection, risk-aversion, etc...

[11] The factors listed in the previous footnote are still relevant here. In addition, Nuscheler and Roeder (2016) report on time preferences as another relevant dimension of heterogeneity of consumers.

2.4. The RECE outcome

In a RECE, each firm chooses its output level to maximize its profits assuming that (i) consumers' expectations about the size of the network, S, is given; and (ii) the output level of the other firms, y, is fixed. Thus for a given expected network size S, each firm's reaction function is obtained by maximizing the profit function $\pi(x, y, S)$ with respect to own output x to obtain the first order condition $a - c - \alpha S - 2bx - by = 0$. Solving for x yields the (network-size dependent) reaction curve for each firm as

$$r(y, S) = \frac{1}{2b}(a - c - \alpha S - by).$$

Plugging $y = (n-1)x$ into $r(y, S)$ yields a unique and symmetric Cournot equilibrium with per-firm Cournot output given S as $x_n(S) = \frac{a-c-\alpha S}{b(n+1)}$.[12] The RECE is then the solution of

$$Z_n(S) = \frac{n(a - c - \alpha S)}{b(n+1)} = S$$

(i.e., a fixed point of $Z_n(S)$). Solving the latter equation yields the RECE industry output as $Z_n = \frac{n(a-c)}{n(b+\alpha)+b}$. Using this industry output yields equilibrium per-firm output, industry price and per-firm profit given by, respectively

$$x_n = \frac{a-c}{n(b+\alpha)+b}\ ,\ P_n = \frac{ab + (b+\alpha)nc}{n(b+\alpha)+b} \text{ and } \pi_n = \frac{b(a-c)^2}{[n(b+\alpha)+b]^2} \tag{2}$$

Denote by

$$W_n \triangleq \int_0^{Z_n} P\left(q, Z_n\right) dq - nC\left(Z/n\right)$$

the Marshallian social welfare associated with a RECE with aggregate output Z_n and expected network size $S = Z_n$. Similarly, consumer surplus at the RECE is given by

$$CS_n \triangleq \int_0^{Z_n} P\left(q, Z_n\right) dq - Z_n P_n.$$

Upon the respective computations, we find that

$$CS_n = \frac{1}{2}Z_n^2 = \frac{n^2(b+\alpha)(a-c)^2}{2[n(b+\alpha)+b]^2} \text{ and } W_n = \frac{n[n(b+\alpha)+2b)](a-c)^2}{2[n(b+\alpha)+b]^2}.$$

As a final remark for use in comparisons below, as the strength of network effects α declines to zero, we recover the regular Cournot equilibrium for this oligopoly. In other words, the Cournot equilibrium variables may simply be obtained by setting $\alpha = 0$ in all of the above corresponding RECE variables, as is easily verified.

3. Market structure and industry viability

This section describes the properties of the RECE and the usual Cournot-type learning dynamics that the literature on network effects has commonly associated with how a RECE might actually realize via a natural learning process on the part of firms. The key property of this process that determines its associated final outcome is its Cournot-type stability, i.e., whether a candidate equilibrium is reached from any initial condition or subset thereof as a limit of this process (Amir and Lazzati, 2011 and Garcia and Resende, 2011).

3.1. Augmented Cournot dynamics and RECE stability

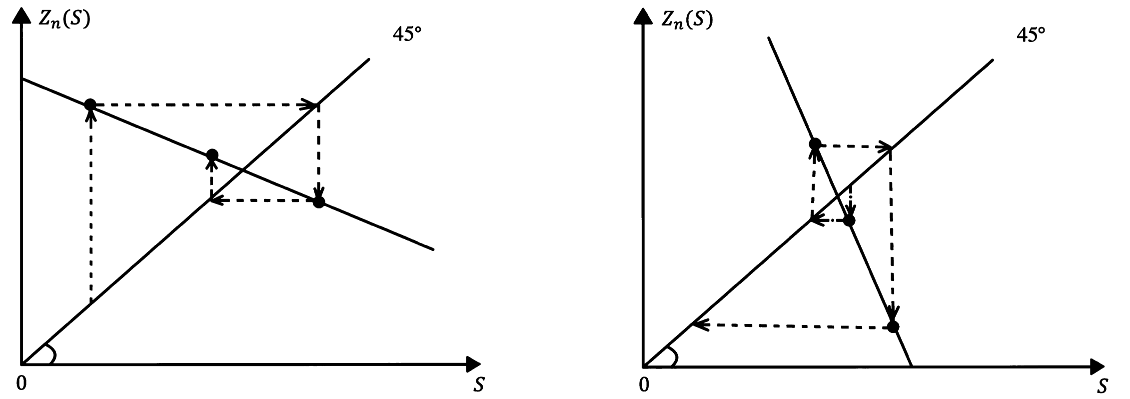
The tacit dynamic process underlying this analysis can be formalized through the following expectations/network size recursion, starting from any initial $S_0 \geq 0$,

$$S_k = Z\left(S_{k-1}\right),\ k = 1, 2, \ldots \tag{3}$$

The process (3) thus begins with a historically given initial network size S_0, then postulates that firms react by engaging in Cournot competition with inverse demand $P(Z, S_0)$, leading to an industry output $Z\left(S_0\right)$, which in turn determines consumers expectation $S_1 = Z\left(S_0\right)$, and the process repeats indefinitely. This yields a sequential adjustment path in which consumers and firms behave myopically with respect to the network size.[13]

[12] We parametrize all RECE outcomes by the number of firms n, treated as an exogenous parameter for future use.

[13] In the far better-known case of positive network (or bandwagon) effect, this process is often referred to as a positive feedback loop.



(a) Stable RECE. (b) Unstable RECE.

Fig. 1. The Cournot Learning Dynamics with Negative Network Externality.

Extrapolating from classical Cournot dynamics (without network effects), we shall think of a RECE (or fixed-point of the mapping $Z_n(S)$) as being globally stable if the process (3) converges to the RECE from any initial S_0. In light of the linearity of the mapping $Z_n(S)$ for the present model and the uniqueness of RECE, there is no distinction between the usual notions of local and global stability, and therefore we may simply write "stable". In the same vein, the RECE will be called unstable if it is not stable or, equivalently, if the process (3) diverges from any initial condition other than the RECE itself, i.e., if $S_0 \neq Z_n$.

A key parameter for the stability analysis is the slope of $Z_n(S)$, or

$$\Delta \triangleq Z_n'(S) = \frac{-\alpha n}{b(n+1)}.$$

It is well known that, as a fixed point of $Z_n(S)$, the RECE is stable if $\Delta > -1$ (or $\frac{\alpha}{b} < \frac{n+1}{n}$) and unstable if $\Delta < -1$ (or $\frac{\alpha}{b} > \frac{n+1}{n}$). Hence, stability depends on both n and α. It follows that, at fixed market structure (i.e., n) and demand slope b, the key parameter for viability is the strength of network effects α, with higher values leading to lower viability, as follows:

(i) With weak network effects ($\frac{\alpha}{b} < 1$), specifically, if the network effect is weaker than the classical law of demand, the RECE is stable and the industry is viable for all n.

(ii) With strong network effects ($\frac{\alpha}{b} > 2$), the RECE is unstable and the industry is non-viable for all n.

(iii) With moderate network effects ($\frac{\alpha}{b} \in (1,2)$), as $\frac{n+1}{n}$ decreases in n, there exists $\overline{n} \geq 1$ such that if $n < \overline{n}$, we have $\frac{\alpha}{b} < \frac{n+1}{n}$ and thus the RECE is stable and the industry is viable and the opposite holds if $n > \overline{n}$. Fig. 1a and 1b provide a visualization of the stable and unstable RECEs.

We analyze these two cases separately, as they lead to vastly different implications for the potential realistic emergence and the properties of RECE.

3.2. Properties of the stable RECE

Here we analyze the properties of the RECE for the case where the learning process (3) is convergent, in terms of its implications for market structure and comparative statics with respect to entry and strength of network effects.

In this subsection, assume that $\Delta > -1$ or $\frac{\alpha}{b} < \frac{n+1}{n}$. Then the steady-state properties of the dynamic process (3) are as follows (the simple proof amounts to solving for a/b or n in $\Delta > -1$ and is thus omitted).

Proposition 1. *If $\Delta > -1$ or $\frac{\alpha}{b} < \frac{n+1}{n}$, which holds if $\frac{\alpha}{b} < 1$, or if $\frac{\alpha}{b} \in (1,2)$ and $n < \overline{n}$, then*

(a) The unique RECE is stable.

(b) From any S_0, the sequence (S_n) is oscillatory and satisfies $|S_k - S_{k-1}| < |S_{k-1} - S_{k-2}|$ for all k, or in other words (S_n) follows a cobweb dynamics converging to the RECE output Z_n.

(c) The case $\frac{\alpha}{b} \in (1,2)$ and $n < \overline{n}$ might be seen as a natural oligopoly with at most $\overline{n}$ firms (and thus a natural monopoly when $\overline{n} = 1$).

Since the RECE is unique and globally stable, postulating it as the plausible outcome of the learning process (3) follows standard practice in the literature on network effects. In addition, the fact that stability requires some form of weak or mild network effects is also a common feature (Katz and Shapiro, 1985 and Amir and Lazzati, 2011). However, the fact that, under mild network effects (or $\frac{\alpha}{b} \in (1,2)$), a sufficiently high industry concentration is also needed is a priori a novel feature. Yet, on second thought, this is intuitive since total output, and thus demand decay, increase with more firms (see next result). In particular, if $\frac{\alpha}{b} \in (\frac{3}{2}, 2)$, then it is easy to see that stability requires $n < 2$, which amounts to requiring n to be equal to 1, i.e., a monopoly industry. This is a new instance of what might be called natural monopoly, induced by the need to avoid instability in the learning dynamics. A similar argument holds for natural oligopoly with a maximum of $\overline{n}$ firms. We shall return to this issue below.

We next derive some comparative statics of market performance with respect to the level of competition and the strength of network effects. We start with the effects of increased competition.

Proposition 2. *As n increases in such a way that the condition $\frac{\alpha}{b} < \frac{n+1}{n}$ is preserved, the usual comparative statics results hold, namely,*
(a) x_n decreases, Z_n increases and P_n decreases.
(b) π_n and $n\pi_n$ decrease, while CS_n and W_n increase.

In interpreting the contents of the comparative statics results, it is useful to keep in mind that a change in an exogenous variable here leads to a shift in the demand function, so that the effect for instance on consumer surplus cannot be made by comparing two different areas under the same inverse demand curve. Despite this departure from standard analysis of oligopoly models, the effects of more exogenous entry into the market are fully analogous to those for the case of regular Cournot oligopoly (for a general treatment of the latter, see Amir and Lambson, 2000).[14] Nevertheless, unlike the latter setting, these results are not a priori as intuitive or easily expected in the present context.[15] The reason is that, being endogenous according to RECE, demand is not fixed as n varies, but variable and in fact shrinking, as n increases. In other words, as more firms enter, the demand function shrinks and each firm must respond to this negative shift in addition to the incremental competition from new rivals. This new demand contraction effect clearly works to lower industry output, and the fact that the latter ends up going up with n nevertheless means that the usual (positive) competition effect is the stronger of the two.

Similar remarks (omitted for brevity) on the role of shifting demand apply to the results on per-firm output, consumer surplus, and social welfare. As for price, looking at $P(Z, S)$, since both arguments of P (capturing the law of demand and the network effects) push for a lower price, this implies at once that the price decreases in n.

Shedding light on the effects of the strength of network effects on RECE outcomes is also a key concern in this paper.

Proposition 3. *As α increases in such a way that the condition $\frac{\alpha}{b} < \frac{n+1}{n}$ is preserved, the comparative statics of market performance is as follows:*
(a) x_n, Z_n and P_n decrease.
(b) π_n, $n\pi_n$, CS_n and W_n decrease.

Overall, the main message of this Proposition is that the overall impact of negative network effects on market performance is detrimental. Viewed as an externality, it is negative for both consumers and producers, and thus for society as a whole. The negative role of network effects is reflected in their downward-shift impact on the demand function. In particular, it is worth stressing that, since the regular Cournot equilibrium corresponds to the RECE outcome with $\alpha = 0$, the former has a better market performance than the latter along every dimension, as a direct consequence of this Proposition.

One especially unusual feature in terms of regular oligopoly logic is that both RECE industry output Z_n and price P_n decrease with higher α. While this might at first appear like a contradiction, it is actually a reflection of the fact that, as α increases, the entire demand function itself shifts downwards, which may well end up driving both industry output and price down. Indeed, each of the above comparative statics exercises involves distinct demand functions. Although the price and the output decreases are a priori a mixed outcome for consumers, consumer surplus overall is still negatively affected, again due to the lower demand under the higher value of α.

3.3. Unstable RECE: non-viability for industries with many firms

Here we analyze the properties of the RECE in case where the learning process (3) is divergent.

The dual condition on Δ flips the steady-state properties of the process (3) as follows (the proof is simply dual to the stable case, in light of the affine nature of the mapping $Z_n(S)$).

Proposition 4. *If $\Delta < -1$ or $\frac{\alpha}{b} > \frac{n+1}{n}$, which holds if $\frac{\alpha}{b} > 2$, or if $\frac{\alpha}{b} \in (1, 2)$ and $n > \overline{n}$, then*
(a) The unique RECE is unstable.
(b) From any S_0, the sequence (S_n) is oscillatory and satisfies $|S_k - S_{k-1}| > |S_{k-1} - S_{k-2}|$ for all k, or in other words (S_n) follows a cobweb dynamics diverging to the output 0.

In this case, the mapping $Z_n(S)$ is too steep (i.e., not a contraction) and therefore the process (3) does not converge to the unique RECE, as given by (2). It follows that the latter cannot emerge as a reasonable equilibrium prediction according to (3). Instead, the process (3) forms an outwardly diverging cobweb from any initial condition and the limit can be seen by inspection to be 0 output.

For the question of the appropriate interpretation of the instability property of RECE here, recall that in game-theoretical models, instability of Nash equilibrium is almost always taken to mean that the equilibrium in question is essentially irrelevant as far

[14] This analogy is meant in a qualitative sense, since the rates of changes of the various variables below do depend on the strength of network effects α.

[15] For comparison, recall that, except for the effect on total output, these outcomes do not necessarily hold in the case of positive network effects as shown via plausible examples in Amir and Lazzati (2011).

as predictive power (or potential realization) is concerned.[16] Since the present model is even more complex, involving a mix of strategic adjustment and rational expectations, we postulate the same conclusion for the unstable RECE outcome.[17]

Furthermore, since the learning process follows an out-spiraling cobweb, the process will end up at zero output. We interpret this limit outcome to mean that the industry will not stabilize under current conditions. In such cases, the industry may be said to be non-viable, an unusual outcome that is not a priori easily expected (Amir and Lazzati, 2011).

3.4. Back to the stylized facts

In this subsection, we relate the above results on market performance under RECE to the evolution of vaccine industries and their stylized facts, as reported in Section 2.[18]

We begin by observing that the unusual outcome of industry non-viability is not caused by the unit production cost being too high relative to demand (the usual cause for non-viability in non-network industries). Rather, it follows from the output fluctuations in the learning process $Z_n(S)$ being too strong, due to a combination of strong network effects and a high number of competing firms, as reflected in the condition $\frac{\alpha}{b} > \frac{n+1}{n}$. Hence, in particular, if a monopolist alone were to serve the market, the industry would be stable and viable for sure, while a sufficiently competitive industry (i.e., with n such that $\frac{n+1}{n} < \frac{\alpha}{b}$) would not be viable. This is a priori quite counter-intuitive with respect to conventional logic since, without network effects, more competitive industries are often thought to be more viable.[19]

Importantly, taken together, Propositions 1 and 4 yield a clear-cut implication that is not a priori intuitive: A given industry with negative network effects may find itself in a natural monopoly or oligopoly with few firms, while the presence of more firms would inexorably lead to an unstable situation that cannot be sustained. This situation of limited competition has persisted despite very high price-cost margins, whereas the high price-cost margin is sustained by the limited competition from Proposition 2. This provocative theoretical prediction appears to be quite consistent with key features of the vaccine industry as described in Stylized Facts #1 and #3.

Furthermore, in line with Stylized Fact #2, the pattern of initial high competition and subsequent exit that has taken place in this industry is also consistent with the idea that instability is a natural corollary of high numbers of firms in the present setting. Since the industry stabilized as a monopoly or oligopoly with few firms, the overall pattern fits both Propositions 1 and 4.

Scherer (2007) provided a thorough analysis of the observed evolution towards excessive concentration, centered around the role of the cost structure in vaccine industries, namely the presence of high fixed costs (pertaining to R&D, development, testing and marketing). While scale economies are indeed broadly recognized to lead to monopoly or restricted competition, they do not explain as readily the evolution of the vaccine industry from an initially large number of competitors to their current few firms. Nor do they explain well why re-entry does not take place after the multi-fold increase in vaccine prices (Arnould and DeBrock, 1996) and the extremely high and persistent price-cost margins (Scherer, 2007).

The present analysis provides an alternative possible explanation derived directly from the role of negative network effects, once these are explicitly recognized as important for both the demand and the supply sides of the industry. A large number of firms may lead to instability of the RECE and thus to non-viability of the associated industry.

Extrapolating from our results, a reasonable conjecture as to why the many firms initially entered the vaccine industry, before undergoing a shake-out, is that they had disregarded the network effects and thought of the industry in terms typically connected with a regular Cournot oligopoly, in which case their evaluation of the prospect for profitability might have been correct if based on well-known conclusions from standard Cournot competition.

4. The first-best solution and public policy

This section considers the key benchmark of first-best planning for a vaccine market, along with some corrective public policy in the form of consumer and producer per unit subsidies as a way to remedy the distortions present in many oligopolistic vaccine markets.

In the game-theoretic models between vaccine consumers discussed earlier, the Nash equilibrium does not involve full vaccination, as long as the cost of vaccination is sufficiently large. In fact, neither does the socially optimal solution (defined without health damage term, in contrast to what we do below) although it calls for more people to vaccinate than at the Nash equilibrium (e.g., Sorensen, 2023 or Heal and Kunreuther, 2005). In both cases, this is intuitive and follows simply from the fact that the vaccine is costly to produce. As our demand function is derived partly from these types of models and serves to bring them into a market

[16] For instance, in a model of two inter-linked game-theoretic models of an economy with multiple equilibria, Matsuyama (2002) uses stability as a selection criterion to rule out (Cournot-unstable) symmetric equilibria. See also Amir and Lambson (2000) for more on this point.

[17] The common practice of discarding unstable equilibria as irrelevant from a practical standpoint in economics is confirmed by much experimental literature. For instance, Holt (1995) reports strong laboratory support for the predictive power of globally stable Cournot equilibrium. Cox and Walker (1998) also found that laboratory behavior confirmed stable Cournot equilibria well, but offered no support for unstable Cournot equilibria of the usual quantity game. Similar results are also reported by Chen and Gazzale (2004) concerning unstable equilibria in a broad class of public good mechanisms.

[18] For a broader perspective, see e.g., Dasgupta et al. (2021).

[19] That viability is indeed a relevant issue in real-life network industries is a key conclusion of the highly insightful book by Rohlfs (2001), which is a collection of case studies on the emergence of several real-life network industries, including specific diagnoses for failed (or non-viable) launches, e.g., for earlier versions of the fax machine, computer disks, etc... (see also Shapiro and Varian, 1998).

context, we would expect similar qualitative conclusions to hold about under-vaccination here. However, unlike past models in general, we also include a health damage term in the first-best analysis to reflect the contagion externality, which makes the setting richer and more realistic (see Dasgupta et al., 2021 and Galiani, 2022).

4.1. The first-best solution

To formulate a proper first-best objective for the social planner, social welfare must include a term to capture the health damage caused by the epidemic via the unvaccinated fraction of the population.[20] Let $\overline{Z}$ stand for the relevant total population. The expected health damage when total output $Z \leq \overline{Z}$ is produced is then postulated as a linear function

$$D(Z) \triangleq d(\overline{Z} - Z), d > 0,$$

where the parameter d measures the expected severity of the infection. This expected damage is meant to include all the treatment, subsequent contagion effects, and other social costs of infection.

This simple linear structure for the damage function is convenient for two separate respects in the present context. First, the actual size of the population will be immaterial to our analysis, since the term $d\overline{Z}$ will not affect our marginal analysis, as will be seen shortly. The second is that, in light of possible underlying uncertainty, linearity implies the desirable property of certainty equivalence.

The social welfare function for a given expected network size S and number of firms n is

$$\begin{aligned} W(Z,S) &= \int_0^Z P(t,S)dt - cZ - d(\overline{Z} - Z) \\ &= \int_0^Z (a - \alpha S - bt)dt - cZ - d(\overline{Z} - Z) \\ &= aZ - \alpha SZ - b\frac{Z^2}{2} - cZ - d(\overline{Z} - Z). \end{aligned}$$

The term $(\overline{Z} - Z)$ captures the number of unvaccinated people.

Taking S and n as fixed, the social planner's objective is to maximize $W(Z,S)$ w.r.t. total output Z. The first order condition w.r.t. Z, $\frac{\partial W(Z,S)}{\partial Z} = 0$, yields

$$P(Z,S) = a - \alpha S - bZ = c - d.$$

The planner's solution involves pricing below marginal cost, which is intuitive as a way to reach a higher vaccination rate in light of the social damage term in the social objective function.

Solving for Z yields $Z^*(S) = \frac{1}{b}(a - c + d - \alpha S)$. The first-best industry output is then a fixed point of $Z^*(S)$, i.e., the solution of $Z^*(S) = S$, which is

$$Z^* = \frac{a - c + d}{b + \alpha}. \tag{4}$$

This fixed-point of $Z^*(S)$ is stable if $Z^{*\prime}(S) = -\frac{\alpha}{b} > -1$ or $\alpha < b$ and unstable if $-\frac{\alpha}{b} < -1$ or $\alpha > b$. Once more, with strong network effects, or $\alpha > b$, the first-best outcome is not stable and thus potentially not a relevant solution from a practical standpoint.[21] Therefore, we assume that $\alpha < b$ for equilibrium stability in this entire section.

4.2. Public policy: a two-part subsidy

This subsection explores the role of government subsidies for vaccines and their capacity for pandemic eradication. In a more realistic, second-best perspective wherein the social planner is not empowered to control market conduct, it could attempt to implement policies that might replicate first-best outcomes, despite the firms continuing to behave according to the RECE concept. In this subsection, we explore the role and the potential for production subsidies to the firms manufacturing vaccines to implement the first-best solution.

The most commonly adopted and realistic options for intervention in a vaccine market are probably consumer and producer subsidy schemes.[22] A production subsidy is defined as a subsidy k per-unit output produced and sold by a firm, satisfying the constraint $0 < k \leq c$.

[20] This is a standard way of integrating negative externalities into an overall welfare objective in a partial equilibrium setting, as in the more widely investigated case of pollution in environmental economics.

[21] In other words, assuming some learning is needed to get to the unique solution, instability is likely to mean that the solution will not be reached. Instead, the analog of the learning dynamics converges to zero output.

[22] Such programs may include special targeted campaigns such as in-house visits (Hirani and Wüst, 2022).

We consider the following scheme: Extend a subsidy k per vaccine produced and sold for each of the n firms in the market and a subsidy γ per consumer who vaccinates, with objectives to bring about the first-best outcome or otherwise get as close to it as possible. In other words, the target is to implement the first-best industry output

$$Z^* = \frac{a-c+d}{b+\alpha}.$$

It is useful to recall that the planner faces three different inefficiency-generating externalities: health or contagion effect (through d), market power (through n) and network effects (through α). The planner's intervention clearly lies in the realm of second-best regulation since, aside from providing the subsidy, the planner does not interfere with firms' market conduct. In other words, firms continue to behave according to the same RECE precepts discussed earlier, the only change being the consumer demand and production cost changes implied by the subsidy.

From a formal standpoint, one can think of these schemes as two-stage games, wherein the planner announces a subsidy $\gamma \in [0,p]$ to each consumer when the price is p and $k \in [0,c]$ to each firm in the first stage, and then the firms compete in RECE fashion to service the vaccine market in the second stage. The profit function of a firm is therefore changed to

$$\pi = x[a+\gamma-\alpha S-b(x+y)]-(c-k)x.$$

In other words, $\gamma \geq 0$ is a price subsidy compensating consumers (thus shifting the demand function up) and $k \leq c$ is a cost subsidy for firms, which reduces production unit cost from c to $c-k$.

We analyze the equilibrium outcomes with this subsidy scheme by simply using our previous calculations as in Section 2.4, upon replacing c by $c-k$ and a by $a+\gamma$.[23] Hence, the RECE is then the solution of $Z_n(S) = \frac{n(a+\gamma-c+k-\alpha S)}{b(n+1)} = S$, and the RECE industry output may be easily calculated to be

$$Z_n(k,\gamma) = \frac{n(a+\gamma-c+k)}{n(b+\alpha)+b}.$$

To validate the regulated oligopoly in terms of stability of its equilibrium outcome, observe that the slope of $Z_n(S)$ with respect to S is not affected by k and γ, so the stability condition remains the same as that given in Section 3 (see Proposition 1), i.e., $\frac{\alpha}{b} < \frac{n+1}{n}$. The latter condition is implied by the stability condition for the first-best solution, i.e., $\alpha < b$.

The optimal subsidy (k^*,γ^*) aiming to induce the first-best outcome can be solved by equating

$$Z_n(k,\gamma) = Z^* = \frac{a-c+d}{b+\alpha}.$$

Hence, a subsidized n-firm oligopoly will produce a RECE equal to the first-best level Z^* when

$$k^*+\gamma^* = d + \frac{b(a-c+d)}{n(b+\alpha)} = d + b\frac{Z^*}{n}. \tag{5}$$

The price paid by consumers is then

$$\widetilde{P} = a-(b+\alpha)Z_n(k^*,\gamma^*) = a-(b+\alpha)Z^* = c-d$$

We consider two separate cases.

Case 1: $c \geq d$.[24] Then the subsidized consumers end up paying $\widetilde{P} = c-d \geq 0$ and multiple pairs (k^*,γ^*) may be found to satisfy (5). Therefore, in this case, the first best is attainable with multiple choices of optimal subsidies. In particular, one meaningful optimal choice of subsidies is $k^* = d$ and $\gamma^* = b\frac{Z^*}{n}$, i.e., a partial production subsidy equal to the unit damage cost d and the remainder $b\frac{Z^*}{n}$ of the total subsidy going to consumers. Alternatively, another optimal choice of subsidies is $k^* = c$ and $\gamma^* = b\frac{Z^*}{n}+d-c$, i.e., a full production subsidy equal to the unit cost c and the remainder of the total subsidy going to consumers.

Without consumer subsidy (i.e., setting $\gamma^* = 0$), the constraint $k \leq c$, along with (5), implies $c-d \geq k^*-d = b\frac{Z^*}{n}$. The latter condition will always hold for sufficiently high values of n, but may or may not hold when n is small. Therefore, if the planner uses only a production subsidy, implementing the first-best outcome is more likely to be possible in more competitive markets (or for high values of n).

Case 2: If $c < d$. Then $\widetilde{P} < 0$, which means vaccines are not only free, but consumers need to be bribed to get vaccinated.[25] Multiple pairs (k^*,γ^*) may be found to fit (5), e.g., give the maximum subsidy to producers, i.e. $k^* = c$, and the rest from (5) to consumers, i.e. $\gamma^* = d-c+b\frac{Z^*}{n}$. Without consumer subsidy (i.e., with $\gamma^* = 0$), (5) implies $k^* > d > c$, which is a contradiction to $k^* \leq c$. Hence, in this case, the two subsidies together are necessary to generate the first-best outcome.

[23] The subsidy may thus also be thought of as research and development, specifically as process R&D, since its final effect is to lower unit production costs. In other words, we may think of the subsidy as pertaining to process R&D.

[24] One might expect that c should be less than d, i.e. that the expected social cost of curing infection ought to exceed the cost of the vaccine for the latter to be a viable option, or in other words, prevention is less costly than (post-infection) treatment. However, this need not hold since vaccines confer private benefits to consumers too.

[25] Monetary incentives to increase COVID-19 vaccinations have been widely used. Campos-Mercade et al. (2021) provides evidence of the positive effects of such bribes in a study of Covid 19 vaccination rates in Sweden. Similar programs were undertaken in several countries, including South Africa, Hong Kong and Serbia. Similar campaigns for other vaccines in Africa (e.g., tetanos) are discussed in Arezki (2021). Even loss of travel and various access rights during the Covid 19 pandemic may be seen in the same vein, though as sticks instead of carrots.

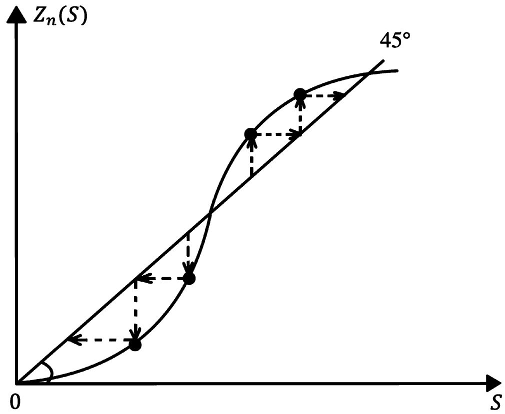


Fig. 2. The Cournot Learning Dynamics with Positive Network Externality.

To summarize, the foregoing analysis has just established the following conclusion.

Proposition 5. *The scope to bring about the first-best outcome by a social planner is as follows.*
(a) A second-best social planner using both production and consumer subsidies can always achieve the first-best outcome.
(b) However, using a production subsidy alone,
(i) the first-best cannot be reached when $d > c$, and
(ii) the first-best may fail to be reached in concentrated markets when $d < c$, but is always possible under sufficient competition.

We now provide a discussion of the implications of this result via a series of remarks. The main conclusion is that a combination of production and consumer subsidies may well be necessary to achieve the first-best outcome in a vaccine industry. A production subsidy alone might work in case of mild epidemics (those with $c \geq d$, i.e., those characterized by less harmful infection for people, less contagion,...), but only for more competitive industries. For more severe epidemics (those with $c < d$, i.e., those with more harmful infection, faster contagion, and long-lasting effects...), both subsidies will definitely be needed, including a direct bribe to consumers.

In addition, since our stylized facts point to vaccine industries typically being rather concentrated, the use of both subsidies will often be required to bring about the first-best outcome under all relevant parameter configurations. This is indeed consistent with the way most societies and the WHO have been dealing with pandemics.

The fact that public policy is aimed at dealing with a pandemic (which motivates the presence of the term d) is important in the analysis above, since, without it, the needed subsidy in (5) would become $k^* + \gamma^* = \frac{b(a-c)}{n(b+\alpha)}$, which would be feasible (i.e., k less than c) for some parameter values. In particular, whenever the vaccine market is sufficiently competitive (i.e., for high enough values of n), the latter optimal subsidy can be made as close to zero as desired, and is therefore feasible. However, the level of competition needed may well exceed what triggers instability of the equilibrium learning process of Section 3. As noted earlier, such favorable levels of competition may also exceed the prevailing ones in the real world for the vaccine industry.

As a final remark, the impossibility result given in the Proposition concerns only the (commonly used) class of production subsidies. Indeed, going beyond this class, i.e., ignoring the constraint $k \leq c$, the social planner may achieve the first-best outcome by using the subsidy k^* given by (5), as was demonstrated above. In such a case, the government would be subsidizing firms beyond covering their production costs, which is certainly not a common form of public policy. Yet, this is nevertheless an implication of the simple analysis here.

4.3. Dynamic pricing implications

In this subsection, we shall extrapolate from our static analysis of the RECE and the planner's solution to reach conclusions of a more dynamic nature regarding a suitable price path over time for vaccine industries (or any industry with negative network effects), with and without subsidies. To this end, we first review the analogous results for the case of industries with positive network effects. The quasi-dynamic learning process (3) tacitly provides some guidance in both cases.[26]

Under positive network effects, non-viability is a well-known issue that was documented in a number of case studies in Rohlfs (2001). It follows from a property of the increasing S-shaped mapping $Z_n(S)$, namely that it starts at zero, crosses the 45° line from below at a network size called critical mass, and then crosses again at a locally stable steady-state, as in Fig. 2 (which is the same as Fig. 1 in Amir and Lazzati, 2011). This common configuration means that the network unravels to zero whenever the initial network

[26] Such an extrapolation is often discussed in the literature on positive network effects.

size is below the critical mass.[27] The appropriate pricing policy for the firms is to price low (or at cost) initially to promptly build enough installed base for the industry to launch successfully and eventually to increase the price later on to harvest the rising demand for the good.

In the present case, the price path progression should be essentially the reverse of the previous case. Namely, firms' prices should be high initially as they would target the high reservation price (or high stand-alone value) consumers first and, additionally, induce declining demand at a lower rate. Prices should be lowered progressively as demand shrinks and lower-value individuals need more of a price break to vaccinate.

If the social planner's subsidies (from Section 4.2) are in place, a similar time path for the price subsidy will be suitable, following an analogous reasoning. In other words, the social planner should offer little or no subsidy to early vaccinees and keep much of the subsidies to be awarded later on to lower-value, reluctant individuals with a tendency to opt for vaccines only after significant lags.[28]

5. Conclusion and policy implications

This section provides a set of conclusive remarks, followed by a number of implications of the present analysis for firm managers as well as for public policy, as well as some open questions for further research.

This paper has presented a novel simple model of oligopolistic competition for the vaccine industry, which explicitly takes into account the market implications of the underlying negative network externalities that were already known in the extant literature. The unique equilibrium appears to capture the three main stylized facts that pertain to this industry: The natural monopoly or oligopoly with few firms as a stable market structure, the emergence of the latter following a shake-out from an initial period with high levels of competition, and unusually high price-cost margins after the shake-out. One possible scenario to explain the (ex post) unwise decision to enter for the firms that ended up undergoing a shake-out is that they were unaware of, or failed to take into account, the negative network effects in such industries.

As significant scale economies are often cited as a factor in favor of natural monopoly, Scherer (2007) argues that the high fixed costs associated with the production of vaccines (in terms of R&D and other development costs) is the main reason behind the high concentration in vaccine industries. However, this explanation does not square well with the fact that the industry initially had high levels of competition before the advent of a shake-out, or with the subsequent fact that re-entry did not take place despite the high price-cost margins that persisted after the shake-out. In other words, had they faced a regular Cournot oligopoly, their survival in that market would not have been jeopardized.

We next draw some useful implications for managers and public policy. In industries with significant negative network effects, the possibility of competition-induced instability and non-viability clearly has direct implications for the key decision of entry, both for the firms' managers and public regulators. For managers, entry is not solely to be decided on the basis of entry costs and strategic profit estimation, but, in light of the network effects, also in terms of implied learning post-entry dynamics. In addition, the anticipation of a natural limit on the number of firms that may serve such an industry (i.e., natural oligopoly) is likely to lead to preemption in the entry process, somewhat akin to what transpires under scale economies or other barriers to entry but through an entirely different and novel mechanism. One would thus expect vaccine industries to confer a first-mover advantage in entry, and thus also in the concomitant R&D needed to serve such markets. One implication might be more severe innovation contests than in regular industries. Another might be a higher propensity for collusion amongst the few survivors, since it is known that collusion tends to break down when many firms compete (Belleflamme and Peitz, 2015).

For second-best public policy on entry, the usual positive impact of more competition on social welfare grounds has to be weighed against the possible instability of the industry due to excessive entry. This trade-off might be exacerbated by the fact that a suitable subsidy program would be cheaper to administer in case of a more competitive industry.

We close with a discussion of some limitations of the present analysis, in the lack of consideration of the following features of interest for vaccine markets. The model does not take into account random fluctuations in the supply of vaccines (Scherer, 2007). This feature may be exacerbated by a natural monopoly/oligopoly, assuming firms' production shocks are independent, as more firms would favor less supply fluctuations, via the Law of Large Numbers. The model also ignores the cost side of the substantial regulatory and liability restrictions on vaccine sales. Finally, there is a robustness issue, as the analysis is based on a specific formulation of a Cournot oligopoly with network effects. These issues would be natural extensions for further work on this topic.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[27] The reasons behind the lack of viability are obviously quite distinct in the present case, since $Z_n(0) > 0$, i.e., 0 is not a trivial RECE in the present case. A key difference between the two cases is that more competition is always beneficial to viability for positive network effects (Amir and Lazzati, 2011), but may be detrimental to industry stability, and thus viability, in the present case. This gives another foundation to natural oligopoly, quite distinct from the classical notions, due to scale economies or endogenous quality differentiation (Shaked and Sutton, 1983).

[28] This time path was indeed what transpired in several countries regarding Covid-19 vaccination, except that the incentives for late vaccinees took the form of threats of loss of various rights (i.e., of sticks instead of carrots).

Data availability

No data was used for the research described in the article.

Appendix A

This appendix contains the proofs of results not given in the text.

Proof of Proposition 2. All the proofs here are based on simple computations, treating n as a real number w.l.o.g.

(a) Starting from the RECE expressions, it can be seen by inspection that $\frac{dx_n}{dn} < 0$ since n only appears in denominator.

Next, differentiating with respect to n yields $\frac{dZ_n}{dn} = \frac{b(a-c)}{[n(b+\alpha)+b]^2} > 0$.

Similarly $\frac{dP_n}{dn} = \frac{b(c-a)(b+\alpha)}{[n(b+\alpha)+b]^2}$, which is < 0 since $a > c$.

(b) Similarly, $\frac{d\pi_n}{dn} < 0$ since n only appears in denominator.

The facts that $\frac{dn\pi_n}{dn} < 0$, $\frac{dCS_n}{dn} > 0$, and $\frac{dW_n}{dn} > 0$ are similar computations left to the reader.

Proof of Proposition 3. It can be seen by inspection that $\frac{dx_n}{d\alpha} < 0$ and $\frac{d\pi_n}{d\alpha} < 0$ since α only appears in denominator.

The facts that $\frac{dn\pi_n}{d\alpha} < 0$, $\frac{dCS_n}{d\alpha} < 0$, and $\frac{dW_n}{d\alpha} < 0$ are similar computations left to the reader.

References

Amir, R., Evstigneev, I., Gama, A., 2021. Oligopoly with network effects: firm-specific versus single network. Econ. Theory 71, 1203–1230.
Amir, R., Lambson, V.E., 2000. On the effects of entry in Cournot markets. Rev. Econ. Stud. 67, 235–254.
Amir, R., Lazzati, N., 2011. Network effects, market structure and industry performance. J. Econ. Theory 146, 2389–2419.
Arnould, R., DeBrock, L., 1996. The application of economic theory to the vaccine market. In: Pauli, M., Robonson, C., Sepe, S., Willian, M. (Eds.), Supplying Vaccine: An Economic Analysis of Critical Issues. IOS Press, Amsterdam.
Arezki, R., 2021. Cash payments in Africa could boost vaccine uptake. Nature, 9.
Belleflamme, P., Peitz, M., 2015. Industrial Organization: Markets and Strategies. Cambridge University Press, Cambridge, U.K.
Ben-Elhadj, N., Jebsi, K., Lahmandi-Ayed, R., 2012. Quality and capacity choices in a vertical differentiation model with congestion. Int. J. Econ. Theory 8, 259–275.
Brandenburg, A., Nalebuff, B., 1996. Co-Opetition. Doubleday, New York.
Brito, D., Sheshinski, E., Intriligator, M., 1991. Externalities and compulsary vaccinations. J. Public Econ. 45, 69–90.
Campos-Mercade, P., Meier, A., Schneider, F., Meier, S., Pope, D., Wengström, E., 2021. Monetary incentives increase COVID-19 vaccinations. Science 374, 879–882.
Chen, Y., Gazzale, R., 2004. When does learning in games generate convergence to Nash equilibria? The role of supermodularity in an experimental setting. Am. Econ. Rev. 94, 1505–1535.
Cox, J.C., Walker, M., 1998. Learning to play Cournot duopoly strategies. J. Econ. Behav. Organ. 36, 141–161.
Danzon, P.M., Pereira, S.N., 2011. Vaccine supply: effects of regulation and competition. Int. J. Econ. Bus. 18, 239–271.
Dasgupta, U., Jha, C.K., Sarangi, S., 2021. Persistent patterns of behavior: two infectious disease outbreaks 350 years apart. Econ. Inq. 59, 848–857.
Galiani, S., 2022. Pandemic economics. J. Econ. Behav. Organ. 193, 269–275.
Gallic, E., Lubrano, M., Michel, P., 2022. Optimal lockdowns for COVID-19 pandemics: analyzing the efficiency of sanitary policies in Europe. J. Public Econ. Theory 24, 944–967.
Garcia, F., Resende, J., 2011. Dynamic Games of Network Effects. Dynamics, Games and Science II: DYNA 2008. Springer, Heidelberg.
Gaumont, D., Badra, Y., Kamburova, D., 2023. Market-dependent preferences, positive and negative network effects and welfare. Math. Soc. Sci. 123, 143–154.
Heal, G., Kunreuther, H., 2005. The vaccination game, Risk Management and Decision Processes Center. Wharton School Working Paper 05-10.
Hellmann, T., Thiele, V., 2022. A theory of voluntary testing and self-isolation in an ongoing pandemic. J. Public Econ. Theory 24, 873–911.
Hirani, J., Wüst, M., 2022. Nurses and infant vaccination coverage. J. Econ. Behav. Organ. 196, 402–428.
Holt, C., 1995. In: Roth, A., Kagel, J. (Eds.), Industrial Organization: A Survey of the Results of Laboratory Experiments. Princeton University Press.
Iverson, T., Karp, L., Peri, A., 2022. Optimal social distancing and the economics of uncertain vaccine arrival. J. Public Econ. Theory 24, 1071–1100.
Katz, M., Shapiro, C., 1985. Network externalities, competition and compatibility. Am. Econ. Rev. 75, 424–440.
Kessing, S.G., Nuscheler, R., 2006. Monopoly pricing with negative network effects: the case of vaccines. Eur. Econ. Rev. 50, 1061–1069.
Leibenstein, H., 1950. Bandwagon, snob, and Veblen effects in the theory of consumers' demand. Q. J. Econ. 64, 183–207.
Matsuyama, K., 2002. Explaining diversity: symmetry-breaking in complementarity games. Am. Econ. Rev. 92, 241–246.
Nganmeni, Z., Pongou, R., Tchantcho, B., Tondji, J.-B., 2022. Vaccine and inclusion. J. Public Econ. Theory 24, 1101–1123.
Nuscheler, R., Roeder, K., 2016. To vaccinate or to procrastinate? That is the prevention question. Health Econ. 25, 1560–1581.
Rohlfs, J., 1974. A theory of interdependent demand for a communications service. Bell J. Econ. Manag. Sci. 5, 16–37.
Rohlfs, J., 2001. Bandwagon Effects in High-Technology Industries. MIT Press, Cambridge, MA.
Scherer, F.M., 2007. An industrial organization perspective on the influenza vaccine shortage. Manag. Decis. Econ. 28, 293–405.
Shaked, A., Sutton, J., 1983. Natural oligopolies. Econometrica 51, 1469–1483.
Shapiro, C., Varian, H., 1998. Information Rules: A Strategic Guide to the Network Economy. Harvard Business School Press, Boston.
Sorensen, A., 2023. The role of vaccine effectiveness on individual vaccination decisions and welfare. J. Public Econ. Theory. https://doi.org/10.1111/jpet.12644.
Veblen, T., 1899. The Theory of the Leisure Class: An Economic Study of Institutions. Macmillan, London.