European Journal of Operational Research 231 (2013) 414–427

Contents lists available at SciVerse ScienceDirect

European Journal of Operational Research

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

Innovative Applications of O.R

Operational issues and network effects in vaccine markets

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ARTICLE INFO

Article history:
Received 12 October 2012
Accepted 22 May 2013
Available online 31 May 2013

Keywords:
Vaccine coverage
Negative network effect
Random yield
Vaccine pricing
Vaccine subsidy

ABSTRACT

One of the most important concerns for managing public health is the prevention of infectious diseases. Although vaccines provide the most effective means for preventing infectious diseases, there are two main reasons why it is often difficult to reach a socially optimal level of vaccine coverage: (i) the emergence of operational issues (such as yield uncertainty) on the supply side, and (ii) the existence of negative network effects on the consumption side. In particular, uncertainties about production yield and vaccine imperfections often make manufacturing some vaccines a risky process and may lead the manufacturer to produce below the socially optimal level. At the same time, negative network effects provide incentives to potential consumers to free ride off the immunity of the vaccinated population. In this research, we consider how a central policy-maker can induce a socially optimal vaccine coverage through the use of incentives to both consumers and the vaccine manufacturer. We consider a monopoly market for an imperfect vaccine; we show that a fixed two-part subsidy is unable to coordinate the market, but derive a two-part *menu* of subsidies that leads to a socially efficient level of coverage.

1. Introduction

Prevention, cure, and control of infectious diseases are important concerns for modern health care systems. The World Health Organization (1999) reports that infectious diseases are the world's biggest killer of young adults and children, and describes them as a "crisis of global proportions... threatening hard-won gains in health and life expectancy." Every one in two deaths in developing countries is caused by an infectious disease; globally, infectious diseases account for over 13 million deaths every year. In 2000, HIV/AIDS, TB, and malaria, together, killed 5.7 million people and caused debilitating illnesses in millions more (World Health Organization, 2002). Influenza and pneumonia claim about 250,000–500,000 lives every year globally, and about 36,000 deaths in the US alone (World Health Organization, 2005). In addition to the emergence of new infectious diseases, such as Severe Acute Respiratory Syndrome or SARS (World Health Organization, 2003), some of the diseases that were once eliminated resurface in populations earlier considered free of the disease. Old infections, such as tuberculosis and diphtheria, have occurred in large epidemics in Europe and other industrialized countries. The 1996 outbreak of polio in Albania, Greece, and the then Federal Republic of Yugoslavia indicates that an infectious disease can easily resurface, if immunization coverage is allowed to drop (World Health Organization, 1999).

Facing these grim realities, variety of epidemic control models have been proposed and used in practice including vaccination programs, prevention programs (such as changing risky behavior), and treatment programs (such as quarantine and use of antivirals); see (Brandeau et al., 2004) for more details. Among a variety of intervention strategies, we focus on *vaccination* programs in this research, as they are well-known for both their efficiency and cost-effectiveness. In fact, the World Health Organization (2000) considers vaccination to be the "ultimate weapon against infection and drug resistance." For influenza (or flu, more commonly), Germann et al. (2006) argue that vaccination, among other control programs such as social distancing, school closure, and use of antivirals, remains the most effective tool to eliminate the epidemic. They show that even if a flu vaccine is poorly matched to the circulating strains, it can still drastically slow down the spread of the disease.

The global vaccination market is a large one, with annual sales of US$21.7 and US$25.3 billion in 2009 and 2010, respectively, and is projected to grow at a compound annual rate of 9.3%, reaching an extraordinary figure of US$39.5 billion in 2015 (Carlson, 2011, 2012). Despite this seemingly large size of the global market and the clear benefits of vaccination programs, vaccine uptakes in populations have typically been low (Blue, 2008). Such undesirably low vaccine coverage can be attributed to two main factors:

Supply-Side Issues: Operational issues on the supply side, such as yield uncertainty, often lead profit-maximizing manufacturers to under-produce, resulting in supply shortages, shortage of influenza vaccines being a prime example. In fact, several

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http://dx.doi.org/10.1016/j.ejor.2013.05.034

papers in the operations management literature argue that the operational risk borne by a manufacturer is one of the main reasons for the shortage of influenza vaccine in the market (Chick et al., 2008; Deo and Corbett, 2009).

Negative Network Effect: A relatively low vaccine coverage can also arise from the *negative network effect* faced by consumers. As the fraction of vaccinated individuals grows, the chance of contacting an infection diminishes. Therefore, the willingness to pay for the vaccine reduces, an effect contrary to the positive network effect, in which the willingness to pay for a product increases with the size of the network (Katz and Shapiro, 1985).

In the end, a traditional *free market* for vaccines may not be socially efficient. On one hand, left to its profit-maximizing ways, a supplier may under-produce, resulting in shortages. On the other, an individual may choose to free ride off the herd immunity, and, consequently, voluntary vaccination may not reach a socially optimal level in the population. We are, therefore, interested in studying the following research questions that arise in this context:

- In the face of yield uncertainty and network effects, what is the socially optimal level of vaccine coverage?
- Is it possible, from a contract theory perspective, to induce the manufacturer and the consumers to achieve that level?
- How does the effectiveness of a vaccine influence the above decisions?
- What roles can governments or global non-profit organizations play here in coordinating the market?

Each of the above issues has been examined in an isolated manner in prior research. Some research in the operations management area has been devoted to the role of supply uncertainty and its effect on the supply chain outcome. For example, Chick et al. (2008) argue that the production risk due to unknown vaccine yields, which is assumed by vaccine manufacturers, is the primary reason for an insufficient supply of influenza vaccine in the market. They design a variant of a cost sharing contract which provides incentives to manufacturers, as well as to governments that purchase vaccines, so that a supply chain achieves an optimal balance between for-profit manufacturer incentives and public health incentives. Deo and Corbett (2009) examine the role of production yield in explaining the limited number of players in the influenza vaccine market. However, these works do not consider the negative network effect and the consumers' willingness to pay for the vaccine. On the other hand, the demand-side issue has started receiving some attention in more recent literature in operations management. For example, Cho (2010) studies consumers' willingness to pay, and Arifoglu et al. (2012) address network externality effects in a similar context. However, the objective of these articles are quite different from the current one, as we are concerned with designing contracts to coordinate the vaccine market.

Epidemic modeling and health economics literature has primarily focused on the negative network externality facing the consumers as a key driver for vaccination levels that are lower than what is socially desirable. For example, Bauch and Earn (2004) provide a game-theoretic analysis of vaccine coverage that considers the negative network effect as well as the necessary epidemiological details. They show that a voluntary vaccination program without any government intervention fails to achieve the vaccination level necessary to eliminate the epidemic. Brito et al. (1991) provide a more comprehensive model in their economic analysis of the situation, but lack the necessary epidemiological details. Geoffard and Philipson (1997) also consider vaccine subsidies with the goal of complete eradication of the disease, but do not consider the cost of production and do not discuss an efficient coordination of the vaccine market. They find that a subsidy program would not be effective at achieving eradication because of network externalities. In a more recent article, Althouse et al. (2010) study how public subsidies can help bring the vaccine uptake to a more efficient level in the case of a disease that is subject to network externalities,[1] but they consider only the consumers—their subsidy is designed to maximize the aggregate consumer utility. Cook et al. (2009) analyze epidemiological and economic field data from two sites in Kolkata, India, to estimate the socially optimal subsidy for a cholera vaccine (disease subject to similar network externalities as influenza).

In most of the prior work, however, vaccine production is either neglected (e.g., Bauch and Earn, 2004; Bauch et al., 2003; Geoffard and Philipson, 1997) or considered as deterministic and exogenous (e.g., Brito et al., 1991). Recently, Mamani et al. (2012) consider the role of governments in market coordination through subsidies in the presence of multiple vaccine manufacturers, but they do not take into account the yield uncertainty inherent in the production process, which, as shown here, has major implications in the subsidy program. In particular, they find that a constant one-part subsidy coordinates the market in a deterministic setting. In extending their results, one would naturally expect that a constant two-part subsidy should align the incentives of different parties under the presence of production uncertainty. Our results, however, indicate that, when the yield is stochastic, a constant two-part subsidy is just *not* sufficient to align both consumer demand and production quantity with the first-best outcome; rather, a menu of subsidies is necessary. The purpose of this research is to bridge this conspicuous gap in the literature by considering yield uncertainty and network externalities together in order to develop a more comprehensive analysis and to provide a more practical coordination scheme.

The remainder of the paper is organized as follows. We discuss related prior work in Section 2. Section 3 develops the modeling framework and examines the market equilibrium. In Section 4, we employ a total social welfare function to identify the socially optimal outcome. Then, in Section 5, we derive a two-part subsidy scheme that induces this outcome. Section 6 concludes the paper and offers directions for future research.

2. Literature review

The topic of network externalities and consumers' willingness to pay in the context of public goods in general, and vaccines in particular, is gaining traction in the operations management community. Cho (2010) considers the issue of consumers' willingness to pay and price elasticity to determine the socially optimal policy for selecting strains that are to be included in an influenza vaccine. This threshold policy is obtained based on a trade-off: On one hand, retaining the current composition of influenza strains could lead to an ineffective vaccine if new strains were to emerge. On the other, including new strains in the vaccine composition could increase the production yield uncertainty. Arifoglu et al. (2012) combine consumption-side externalities with the supply uncertainty, and show that the limited availability of vaccines lead to an inflated demand. They quantify the level of ineffectiveness of the decentralized model with partially centralized scenarios. In this paper, we, too, combine negative network effects with yield uncertainty to identify the level of inefficiency in a market-based system. However, unlike Arifoglu et al. (2012), we investigate this inefficiency with the lens of contract theory to design incentive

[1] The role of subsidies in market coordination has also been studied in other contexts that exhibit network effects. For example, within the context of security, Zhuang (2010), Zhuang et al. (2007) show that providing fully subsidized security to targeted agents (with heterogeneous time preferences) can reduce the total social cost of security and improve the performance of the system.