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Designing an intervention strategy for public-interest goods: The California electric vehicle market case ☆

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ABSTRACT

We study the intervention problem for public-interest goods. Public-interest goods are known as goods with positive externalities, allowing the consumer as well as others who do not pay for them benefit from the consumption. Health related goods, such as vaccines, or products with less carbon emissions are well known examples. We consider a supply chain for such a product. Generally, wider adoption or usage of such goods is ensured by the intervention of a central authority in their supply chain. We explore the problem for a setting composed of a retailer and a central authority. The main goal of the central authority is to design and fund an intervention scheme so that decisions of the channel are in line with the good of society, specified as a social welfare function. We propose two intervention tools applied simultaneously: (1) investing in demand-increasing strategies, which affects the level of the stochastic demand in the market; and (2) rebates that affect revenue per unit received by the retailer. We introduce a model that determines a utility maximizing intervention scheme and further investigate the model. We also present two decentralized approaches as benchmarks. Finally, we conduct a case study for California's electric vehicle market and validate our findings by a detailed analysis of the results, including comparisons with the current practice.

1. Introduction

This study is motivated by public-interest goods, which can also be referred as goods with positive externalities. Health related products, energy efficient appliances, and recent developments in green technology (e.g., electric vehicles, solar panels, etc.) are some notable examples. A distinguishing property of these types of goods is that in addition to consumers, third parties (who do not pay for them) enjoy the benefits of their consumption. For instance, people who get the influenza vaccination reduce the chances of non-vaccinated people getting the flu. As the examples indicate, the usage of public-interest goods tremendously benefits individual customers and the majority of the society, so a central authority usually intervenes in the supply chain for the good of the system. Significant examples of intervention include the intervention of the US government, the World Bank, the Global Fund to Fight AIDS, and Tuberculosis and Malaria in distributing medicines, vaccines, and fortified foods to countries in need [33]; the intervention of the German government in the solar panel market [25]; the intervention of the French government in conjunction with the European Union in the petro-chemical industry to encourage biofuel production [4]; and the intervention of the US government and states in the electric vehicle market [37]. The ultimate role of a central authority in such cases is to design and fund an intervention scheme that will enable the chain to choose decisions for the benefit of the society, social welfare. The key question, then, is how to design an intervention scheme that maximizes social welfare.

This paper considers a general setting composed of a retailer and a central authority that regulates the system through an intervention scheme. The intervention has the goal of maximizing expected utility (social welfare) rather than only maximizing expected profit. A critical consideration in designing an intervention mechanism is how it should be incorporated into the system. One alternative is to invest in demand-increasing strategies, such as advertising, education, research and development, and awareness campaigns, so that the demand pool is enhanced in the medium to long run. Another alternative can be either offering rebates to customers or administering subsidies to each unit sold. In fact, rebates and subsidies per unit sold operate similar to each other in terms of improving availability of the product at the retailer via increased unit revenue, and at the same time making the good more attractive for the customers given the level of their willingness to pay. So, we refer to the second intervention tool as rebates in the rest of the paper. Analysis of interventions through

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subsidies or rebates is common in the literature, especially for public-interest goods. For example, Raz and Ovchinnikov [30] consider an intervention mechanism consisting of rebates and subsidies for a general class of public-interest goods; Mamani et al. [27] consider a subsidy program to achieve optimal vaccination coverage, and Lobel and Perakis [25] consider subsidies to achieve a desired adoption target for solar photovoltaic technology. Our work is the first to consider alternative strategies for intervention, affecting both supply and demand. Specifically, we propose a joint mechanism, where the central authority uses investment in demand-increasing strategies and rebates simultaneously. In some sense, then, the problem is to decide on the optimal allocation of the central authority's budget among these two intervention tools.

We formulate this framework via bilevel programming. A bilevel programming problem is a hierarchical optimization problem that includes two mathematical problems within a single instance, one of which is part of the constraints of the other. To summarize, an upper-level decision maker or leader makes his optimal choice first and then a lower-level decision maker or follower makes his decision by optimizing his objective given the dominant player's action. A distinguishing property of this programming is that each player's decision is affected by the other's decision, but is not completely controlled by it (see [10,3] for more details). In our case, the central authority is the leader, whose objective is to maximize social welfare, whereas the retailer is the follower, whose objective is to maximize expected profit. The central authority decides on the direct investment amount for the demand-increasing strategies and on the rebate amount per unit, then the retailer decides on the order quantity. There are few well-documented cases of direct investment response functions, but they are generally assumed to be concave for advertising (e.g. [19,22,1,23]), and we follow the same assumption in this paper. The concave response function indicates that as the money invested increases, so does the expected demand, but with a monotonically diminishing rate. On the other hand, the retailer's problem is a newsvendor problem incorporating the rebate amount. The retailer decides on the profit maximizing order quantity. In addition to developing the modeling perspective, we characterize the optimal intervention strategy and provide useful insights for regulating these goods. We also present three benchmark approaches: one is a no-intervention case and two are decentralized approaches that work with a predetermined rebate amount. Finally, we provide a detailed case study for the California electric vehicle market that assesses the performance of our approach relative to the current mechanism and the applicability of the proposed model.

The first contribution of this paper is using bilevel programming for modeling a newsvendor environment with welfare implications. Designing a joint mechanism consisting of investment in demand-increasing strategies as an additional intervention tool and considering a budget are also novel. Further, we introduce several variations of the model as benchmarks. Finally, we conduct a case study to analyze the benefit of using the proposed mechanism by implementing a novel parameter calibration approach.

The remainder of the paper is organized as follows. Section 2 summarizes the related work in the literature, Section 3 presents our model, along with highlights of some analytical results, Section 4 introduces benchmark approaches, Section 5 proceeds with a case study and computational results, and finally, Section 6 presents concluding remarks.

2. Literature review

This paper considers the supply chain of a public-interest good, hence it is closely related to the literature on economics and operations management.

The economics literature has focused on policy design for regulating monopolies in the public-interest (see [17,34] for further details). Subsidy, tax, and lump-sum transfers are frequently used as public policy instruments in welfare economics. The details on how they are used and their effects on the economy are discussed thoroughly in [16]. Moreover, the impact of intervention tools (such as subsidies and advertising) for accelerating the diffusion of a new product is investigated in the literature. In this context, government is concerned with maximizing the number of adopters while determining the intervention scheme. Here, the intervention tools directly affect the adoption level. On the other hand, in our paper we study the intervention problem in a newsvendor setting, thus the tools are affecting the order quantity. Some examples from this stream of literature are: [14,18,11]. Horsky and Simon [14] examine the effect of firm's advertising strategy on the adoption level of a new product, whereas Kalish and Lilien [18] study the problem of determining a time dependent subsidy scheme under a predetermined government budget. In a recent study, De Cesare and Di Liddo [11], innovation diffusion problem is examined for a Stackelberg game. The government chooses the subsidy amount given a predetermined budget, whereas the monopolist producer determines the pricing and advertising strategies.

There is a stream of studies that deals with incentive mechanism and multi-agent decision making for hierarchical systems in the context of operations. In hierarchical systems such as supply chains, health care systems or service organizations, each stage attempts to maximize its own profit, which nevertheless may not coincide with the optimal decisions for the entire system. Two early examples of such studies are Schneeweiβ [31] and Schneeweiss [32]. The latter is a review of more general systems, where decisions are taken in a distributed manner under available information for each agent. Additionally, such systems can be analyzed under varying decision time scales and asymmetric information availability of agents [39,40]. Compared to this stream of literature, our approach considers a central authority with all available information.

When we look at the supply chain literature, we see an extensive literature focusing on the impact of incentives on the echelons in a newsvendor environment. Instead of welfare/utility implications, they focus on the profits of firms while designing contracts. (See [5] for a detailed review of the supply chain contracting literature.) Although the problem under consideration is a typical problem seen in various settings, studies that combine an intervention mechanism and social welfare in a newsvendor setting are scarce and generally focus on a certain product (usually vaccines) and consider subsidies or rebates as intervention tools.

Refs. [8,12,27,2] are some examples that analyze welfare implications in the vaccine market while determining the optimal coverage level. All these studies consider specific details of the vaccine market, such as infection dynamics and/or yield uncertainty. Chick et al. [8] assume that demand is exogenous to their model, whereas Deo and Corbett [12] assume that the price is set after yield is realized. However, Arifoğlu et al. [2] and Mamani et al. [27] incorporate consumer behavior in this context. The features of the above-mentioned studies make them inapplicable to other types of public-interest goods. Regarding health related products, Taylor and Xiao [33] study design of subsidies from the perspective of a donor with a budget constraint for improving the availability of malaria drugs. The authors show that the optimal subsidy scheme of donor should include only purchase subsidy

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