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A principal–agent problem with heterogeneous demand distributions for a carbon capture and storage system

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A B S T R A C T

Mechanism design problems optimize contract offerings from a principal to different types of agents who have private information about their demands for a product or a service. We study the implications of uncertainty in agents' demands on the principal's contracts. Specifically, we consider the setting where agents' demands follow heterogeneous distributions and the principal offers a menu of contracts stipulating quantities and transfer payments for each demand distribution. We present analytical solutions for the special case when there are two distributions each taking two discrete values, as well as a method for deriving analytical solutions from numerical solutions. We describe one application of the model in carbon capture and storage systems to demonstrate various types of optimal solutions and to obtain managerial insights.

1. Introduction

We study the principal–agent problem in the context of a seller or a service provider (principal) who offers a menu of contracts to buyers (agents) whose demands for the product or service are uncertain. At the time the contracts are offered, agents have private information that helps them select one based on their demand distribution, though actual demand is realized later. This paper formulates the principal–agent problem when the agents can have multiple possible demand distributions, with each distribution consisting of multiple discrete demand levels. We will refer to the different distributions as "types" and the demand realizations within each distribution as "levels".

We refer to a "contract" as a set of options offered towards a particular distribution type, with each "option" targeted towards a particular demand level. Once an agent commits to a contract, they can choose particular options at each time period depending on their demand realization. A "menu" of contracts is offered at the contracting stage (time zero), with each contract geared towards a different demand distribution. The agent chooses a contract from the menu at time zero given their private knowledge of their demand distribution, and then must choose from options within that contract at later time periods, which we refer to as the implementation stage.

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Considering heterogenous demand distributions is important for multiple reasons. The first is that the demand distribution of the agents may be private information, but the principal can estimate a few possible distributions. The second reason is that the principal may choose to engage with multiple agents at the same time, with each agent having a possibly different demand distribution. Our model maximizes the expected profit across potentially multiple agents with different demand distributions. The classical mechanism design problem with incomplete information (Maskin & Riley, 1984) is a special case where the are many types of agents, where each type of agent has a deterministic consumption level which is the agent's private information. Our work adds to the existing literature by considering when agents' consumption levels are stochastic.

When the utility function of the agents is concave and increasing in quantity, the problem can be formulated as a convex optimization problem and can be easily solved numerically for an arbitrary number of distribution types and demand levels. We obtain analytical solutions for the case of a single type agent who has two demand levels, which we refer to as the "single agent-type" problem. The optimal solutions suggest that the principal either chooses to serve both demand levels or only the higher demand level. We also derive analytical solutions for the case of two types each with two levels, and we refer to this as the "dual agent-type" problem. We show that the structure of the optimal solution to the dual agent-type problem not only depends on the demand distributions, but also the ordering of the demand levels across distributions.

Optimal solutions are classified into four categories: separating contracts, non-participating options, pooling options, and a single contract. Separating contracts describe the solutions when four separate options are offered to completely differentiate the demand levels across the two agent types. Non-participating options refer to when the low demands are intentionally not being served. Pooling options occur when the same option is offered toward two different demand levels. Two types of single contract solutions exist, one where the principal has the intention to only serve one type of agent, while the other has three options which serve both agent types. Further, we show that providing a higher than efficient quantity and a subsidy toward the highest demand level can also emerge as the optimal solution, but it is never optimal in the single agent-type problem.

The motivating context for this problem is the design of contracts for carbon capture and storage (CCS) systems. CCS is a process of capturing CO_2 from major point sources, like fossil fuel plants and factories with major CO_2 emissions, before it is released to the atmosphere. The captured gas can then be compressed and transported to special storage sites where it is injected deep underground, into places like depleted oil and gas reservoirs or unmineable coal areas. The sequestered CO_2 is stored indefinitely, and therefore does not increase atmospheric concentrations.

In an effort to mitigate the potential impacts of greenhouse gas emissions to the atmosphere, significant research on low-carbon energy technologies has been conducted. However, given the magnitude of global dependence on carbon-intensive fuels, no single technology has been identified as sufficient to meet the challenge alone and thus multiple solutions are required. CCS methods are projected to be a significant player among many options to reduce carbon emissions, as in Pacala and Socolow (2004), and are needed as part of a cost-effective portfolio of tools to reduce emissions (Kriegler et al., 2014). There currently are dedicated CCS storage sites in Sleipner, Norway (since 1996), Snohvit, Norway (2008), and most recently Quest, Canada (2015). There are two more in construction and expected to come online in 2017 in Gorgon, Australia and Decatur, USA. CCS is also used in conjunction with enhanced oil recovery projects. For a list of CCS projects worldwide, see Global CCS Institute (2017).

In the context of operating CCS systems, the principal is the CCS storage operator who transports and stores CO_2 from emissions sources (called "emitters" henceforth). The agents are the emitters who demand CO_2 storage to avoid emissions penalties. Depending on the variation in demand for power, these emitters' demands change from one period to the next. Different emitters may have different demand distributions due to varying CO_2 capture technologies. In order to incentivize the emitters to participate in CCS, the storage operator designs a menu of contracts with multiple options, each option corresponding to a demand realization. At the contracting stage, an emitter reveals his demand distribution by selecting the contract designed for his type. In the implementation stage, the emitter selects the best option depending on the demand realization. A nominal non-participating option is always offered, so that an agent who commits to a contract can still choose not to pay for the service in that time period.

Our work contributes to the literature in two ways. First, we consider incentives with heterogeneous agents. That is, while an agent privately observes his type (his demand distribution), the actual consumption decision is described by a state of nature that is unobservable at the contracting stage. Therefore, the agent selects the contract that maximizes his *expected* utility. The principal needs not only to offer a contract that induces the agent to report his type truthfully, but also to ensure that once the agent's demand level is realized, the agent is incentivized to select the option designed for that demand level from the contract he has committed to. As a result, the principal faces a dynamic adverse-selection problem due to information asymmetry.

Second, we show how to derive closed-form solutions from numerical results for these nonlinear principal–agent problems. This solution method is free of any assumption on the distributions of agents' consumption needs. There are a large number of possible formats for the analytical optimal solution, and the mapping from the input space to each solution is not well-defined. We plot the mapping from the input space to the analytical solution to give intuition about when certain contract types (separating contracts, pooling options, non-participating options, and single contracts) are likely to be optimal. Finally, we analyze the optimal solutions for more general cases where there are more than two types of agents.

The rest of the paper is organized as follows. Section 2 reviews relevant literature. In Section 3, we present the model and solutions to a single agent-type with a bi-level distribution, and describe a general formulation for multiple distributions and any number of demand levels. In Section 4, we discuss the categories of solutions for the dual agent-type problem with different bi-level distributions under two scenarios, one with the low demand level of the high type greater than the high demand level of the low type (non-overlapping case), and another with the low demand level of the high type smaller than the high demand level of the low type (overlapping case). Numerical results over a range of values of input parameters are presented in Section 5. Section 6 summarizes the managerial insights, and Section 7 concludes the paper.

2. Literature review

Our work relates to three areas in the literature: the principal–agent framework, CCS systems, and carbon taxes. In the classic framework of principal–agent problems, agents are assumed to privately observe their types (valuation, quality or demand) or efforts asserted by agents are not verifiable given a stochastic nature. Facing the presence of information asymmetry or a moral hazard, the principal offers a menu of contracts from which the agents will select the ones that maximize their utilities. Maskin and Riley (1984) show that a nonlinear price-quantity schedule can discriminate among a set of buyers with discrete types under information asymmetry as long as the single-crossing property holds. In the optimal schedule, the highest type agent is offered the efficient amount, and agents with higher types receive higher information rent than those with lower types. Further, two or more adjacent types may receive the same price and quantity.

In dealing with the presence of a moral hazard, obtaining tractability has been difficult. Much effort has been devoted to investigating structural properties and finding the conditions under which principal–agent problems can be solved analytically (Carlier & Dana, 2005; Conlon, 2009; Grossman & Hart, 1983; Holmstrom & Milgrom, 1987; Jewitt, 1988; Mirrlees, 1999; Page Jr, 1991).

The methods and results of both information asymmetry and moral hazard problems have been widely adopted to study various important topics in de-centralized supply chains. Tsay (1999) evaluates the effectiveness of quantity flexibility contracts to deter a retailer from his tendency to overpredict demand to his supplier. Corbett and DeCroix (2001) examine the role of shared-savings contracts between a supplier and a manufacturer in a double moral hazard problem. Cachon and Lariviere (1999) investigate the abilities of several allocation mechanisms to induce truth telling from retailers when the supplier's capacity is limited while Erkoc and Wu (2005) and Özer and Wei (2006) study contracts that encourage suppliers to make optimal capacity decisions for the supply chain. Iyer, Schwarz, and Zenios (2005) examine the optimal