Government Leasing Policy
and the Multi-Stage Investment Timing Game
in Offshore Petroleum Production[1]

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Abstract

Petroleum production involves dynamic and strategic decision-making. This paper describes our research modeling, estimating and analyzing the efficiency of the decisions of petroleum-producing firms in the Gulf of Mexico and Alaska, and examining the impact of government policy on these decisions. In the Gulf of Mexico, inefficiencies may arise when individual petroleum-producing firms make their exploration and development investment timing decisions, as positive information externalities and negative extraction externalities may lead them to interact strategically with firms owning neighboring tracts of land. To empirically analyze these externalities and assess the effects of federal leasing policy, a structural econometric model of the firms' multi-stage investment timing game is developed and estimated. In Alaska, the efficiency of petroleum production may be influenced by tax and leasing policies and contract structures. Our research investigating the effects of institutions and government policy on how energy firms make strategic decisions is important for several reasons. First, our work examines and quantifies the sources of existing inefficiencies in energy markets. Second, our examination of how institutions and policy affect the degree of strategic interaction and the extent of the inefficiencies will enable us to design institutions and policy that lead to socially desirable outcomes that incorporate such socially desirable objectives as efficient petroleum production, environmental protection, energy security, and the desire to transition to alternative sources of energy.

Keywords: petroleum production, energy policy, investment timing game, structural econometrics
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1   Introduction

In order to maximize profits, petroleum-producing firms make decisions that are dynamic and strategic in nature, and that take into account constraints imposed by the regulatory and institutional environment. This paper describes our research modeling, estimating and analyzing the efficiency of the decisions of petroleum-producing firms in the Gulf of Mexico and Alaska, and examining the impact of government policy on these decisions.

Petroleum production is a multi-stage process involving sequential investment decisions. The first stage is exploration: when a firm acquires a previously unexplored tract of land, it must first decide whether and when to invest in the drilling rigs needed to begin exploratory drilling. The second stage is development: after exploration has taken place, a firm must subsequently decide whether and when to invest in the production platforms needed to develop and extract the reserve. Because the profits from petroleum production depend on market conditions such as the oil price that vary stochastically over time, an individual firm producing in isolation that hopes to make dynamically optimal decisions would need to account for the option value to waiting before making either irreversible investment (Dixit & Pindyck, 1994). After investments in drilling rigs and production platforms have been made, the third stage of production is extraction.

The dynamic decision-making problem faced by a petroleum-producing firm is even more complicated when its profits are affected not only by exogenous market conditions, but also by the actions of other firms producing nearby. When firms own leases to neighboring tracts of land that may be located over a common pool of reserve, there are two types of externalities that add a strategic (or non-cooperative)[3] dimension to firms' investment timing decisions and may render these decisions socially inefficient.[4] The first type of externality is an *information externality*: if tracts are located over a common pool or share common geological features so that their ex post values are correlated, then firms learn information about their own tracts when other firms drill exploratory wells or install production platforms on neighboring tracts (Hendricks & Porter, 1996). The information externality is a positive one, since a firm benefits from its neighbors' information.[5] A second type of externality is an *extraction externality*: when firms have competing rights to a common-pool resource, strategic considerations may lead them to extract at an inefficiently high rate (Libecap & Smith, 1999a; Libecap & Wiggins, 1985). The extraction externality is a negative one, since it induces a firm to produce inefficiently. Owing to both information and extraction externalities, the dynamic decision-making problem faced by a petroleum-producing firm is not merely a single-agent problem, but rather can be viewed as a multi-agent, non-cooperative game in which firms behave strategically and base their exploration and development policies on those of their neighbors.

In this paper, we summarize the previous work of Lin (2007) on whether a firm's investment timing decisions and profits in the Gulf of Mexico depend on the decisions of firms owning neighboring tracts of land. Do the positive information externalities and negative extraction externalities

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[3]In this paper, we use the terms "strategic" and "non-cooperative" interchangeably.

[4]In our broad definition of an externality, we say that an externality is present whenever a non-coordinated decision by individual firms is not socially optimal.

[5]Although the information externality has a positive effect on a firm's profits, it is socially inefficient. For example, it may cause firms to play a non-cooperative timing game that leads them to inefficiently delay production, since the possibility of acquiring information from other firms may further enhance the option value to waiting. If firms are subject to a lease term by the end of which they must begin exploratory drilling, or else relinquish their lease, then the information externality would result in too little exploration at the beginning of the lease term and duplicative drilling in the final period of the lease (Hendricks & Porter, 1996; Porter, 1995). In contrast, the optimal coordinated plan would entail a sequential search in which one tract would be drilled in the first period and, if productive, a neighboring tract is drilled in the next (Porter, 1995).

have any net strategic effect that may cause petroleum production to be inefficient? We then describe our ongoing research analyzing the efficiency of petroleum production in Alaska.

To examine investment decisions in the Gulf of Mexico, we develop and estimate a structural econometric model of the firms' multi-stage investment timing game. To analyze petroleum production in Alaska, we develop a dynamic model of the unit operators' production decisions.

Our research investigating the effects of institutions and government policy on how energy firms make strategic decisions is important for several reasons. First, our work examines and quantifies the sources of existing inefficiencies in energy markets. Second, our examination of how institutions and policy affect the degree of strategic interaction and the extent of the inefficiencies will enable us to design institutions and policy that lead to socially desirable outcomes that incorporate such socially desirable objectives as efficient petroleum production, environmental protection, energy security, and the desire to transition to alternative sources of energy.

2 The Gulf of Mexico

2.1 Contributions to existing literature

The exploration timing game in offshore petroleum production in the Gulf of Mexico has been examined in a seminal series of papers by Kenneth Hendricks, Robert Porter and their co-authors (see e.g. Hendricks & Kovenock, 1989; Hendricks & Porter, 1993; Hendricks & Porter, 1996). These papers focus on the information externality associated with exploratory drilling. They analyze this externality and the learning and strategic delay that it causes by developing theoretical models of the exploration timing game. In addition, Hendricks and Porter (1993, 1996) calculate the empirical drilling hazard functions for cohorts in specific areas, and study the determinants of the exploration timing decision and of drilling outcomes. According to their results, equilibrium predictions of plausible non-cooperative models are reasonably accurate and more descriptive than those of cooperative models of drilling timing.

The structural econometric analysis presented in Lin (2007) improves upon the existing literature on the exploration timing game in offshore petroleum production in several ways. First, unlike the theoretical models and reduced-form empirical analyses conducted by Hendricks, Porter and their co-authors, a structural approach yields estimates of the structural parameters of the discrete choice dynamic game. With these structural parameters, one can identify the effects of a neighbor's exploration and development decisions on the profits a firm would get from developing its tract.

A second way in which Lin's (2007) method contributes to the existing literature on the information externality in offshore petroleum production is that it combines the externality problem with real options theory. Oil production is a multi-stage process involving sequential investment decisions. Since the decision to explore a reserve entails an irreversible investment, the value of an unexplored reserve is the value of the option to invest in exploration. Similarly, the value of an explored but undeveloped reserve is the value of the option to invest in development. There is thus an option value to waiting before making either investment because the value of a developed reserve can change, either because exogenous conditions such as the oil price might change, or because there is a chance that neighboring firms might explore or develop first. Moreover, because these two types of investment are made sequentially, they act as compound options: completing one stage gives the firm an option to complete the next (Dixit & Pindyck, 1994).

While literature on the financial theory of option valuation is abundant, structural models applying the theory to the oil production process that account for strategic considerations have yet to be developed. Hurn and Wright (1994) test reduced-form implications of the theory via a hazard model, but neither estimate a structural model nor account for possible strategic interactions. Paddock, Siegel and Smith (1998) compare the option valuation estimate of the market value of selected offshore petroleum tracts with estimates from other valuation methods and with the winning bids, but do not account for either information externalities or extraction externalities. Similarly, Pesaran (1990) estimates an intertemporal econometric model for the joint determination of extraction and exploration decisions of a "representative" profit-maximizing oil producer, but does not examine the case of multiple producers that may interact strategically.

The third innovation this paper makes to the existing literature on the information externality in offshore petroleum production is that while the existing literature focuses exclusively on externalities that arise during exploratory drilling, Lin's (2007) model allows for extraction externalities as well as information externalities that arise during both exploration and development. If firms do indeed learn about the value of their own tracts from the actions of their neighbors, then one would expect firms to update their own beliefs not only if their neighbors begin exploratory drilling, but also if, after having already begun exploring, the neighbors then decide to install a production platform. That a neighbor has decided to begin extracting after it explored should be at least as informative as the initiation of exploration in the first place. Furthermore, extraction externalities are another form of spillover that is not accounted for by previous studies of the investment timing game, and, unlike the information externality, is one that may have a negative effect on a firm's profits.

In addition to the literature on the information externality, a second branch of related literature is that on econometric models of discrete dynamic games (see e.g. Aguirregabiria & Mira, 2006; Bajari, Benkard & Levin, forthcoming and references therein). In particular, Lin's (2007) work applies a method developed by Pakes, Ostrovsky and Berry (2005) for estimating parameters of discrete dynamic games such as those involving firm entry and exit. This paper builds upon the work of Pakes et al. (2005) in several ways. First, unlike their paper, which uses simulated data, Lin (2007) estimates a discrete dynamic game using actual data. Second, while the entry and exit decisions they examine are two independent investments, the exploration and development decisions Lin (2007) examines are sequential investments: the decision to invest in development can only be made after exploration has already taken place. Thus, unlike the one-stage entry and exit games, the investment timing game is a two-stage game. The sequential nature of the investments is an added complexity that Lin (2007) addresses in her econometric model. Third, whereas the estimators Pakes et al. propose are for infinite-horizon dynamic games, the exploration stage of petroleum production is a finite-horizon dynamic optimization problem: firms must begin exploration before the end of the five-year lease term, or else relinquish their lease. As a consequence, an appropriate modification to the estimation algorithm is required. A fourth innovation Lin (2007) makes is that, unlike Pakes et al., she does not assume that the profit function is a known function of the underlying state variables, but instead estimates its parameters from data. While Pakes et al. are able to appeal to economic theory to posit an exact form for profits as a function of state variables such as the number of firms in the industry, she cannot. No economic theory predicts the relationship between profits and such state variables as whether or not a firm's neighbors explore or develop. Indeed, since the relationship between profits and the actions of one's neighbor is among the very parameters she hopes to identify, she chooses to estimate this relationship from the data rather than impose it *a priori*. The task of estimating these additional parameters requires the use of additional moment conditions.

There are several advantages to using a structural model. First, a structural model enables

the estimation of all the structural parameters of the underlying dynamic game. These parameters include not only those governing the relationship between various state variables and the profits of firms, but also parameters governing the distribution of tract-specific private information. Second, the structural model addresses the endogeneity problems without the need for instruments. Measuring neighbors' effects is difficult owing to two sources of endogeneity. One source is the simultaneity of the strategic interaction: if tract i is affected by its neighbor j, then tract j is affected by its neighbor i. The other arises from spatially correlated unobservable variables (Manski, 1993; Manski, 1995; Robalino & Pfaff, 2004). Because the structural model is based on the equilibrium of the underlying dynamic game, however, it addresses the simultaneity problem directly by explicitly modeling the firms' strategies. Moreover, the problem of spatially correlated unobservables can be addressed by interpreting the profits in the model as expected profits conditional on observables. A third advantage to a structural model is that it enables one to estimate how a firm's profits are affected by the decisions of its neighbors; the sign of the effect indicates the net sign of the information and extraction externalities. Fourth, the structural model enables one to explicitly model each of the stages of the multi-stage dynamic decision-making problem faced by petroleum-producing firms.

2.2   The multi-stage investment timing game

In Lin's (2007) model of the investment timing game, each "market" k consists of an isolated neighborhood of adjacent tracts i that were each leased to a petroleum-producing firm on the same date. Time t denotes the number of years after the lease sale date. Firms must begin exploration before time T, the length of the lease term, or else relinquish their lease. Let the "lease term time" τ_{kt} of market k at time t be given by:

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\tau_{kt} = \left\{ \begin{array}{ll} t & \text{if} \quad t = 0, 1, ..., T-1 \\ T & \text{if} \qquad \quad t \geq T \end{array} \right.
$$

For each market k, the state of the market t years after the leases began is given by a vector Ω_{kt} of discrete and finite-valued state variables that are observed by all the firms in market k and as well as by the econometrician. Let θ denote the vector of parameters to be estimated.

At the beginning of each period t, the owner of each tract i must make one of two investment decisions. If tract i has not been explored before time t, its owner must decide whether to invest in exploration at time t. If tract i has been explored but has not been developed before time t, its owner must decide whether to invest in development at time t. For each period t, all firms make their time-t investment decisions simultaneously.

Each firm's time-t investment timing decision depends in part on the state of the market $\Omega_{kt} \equiv (N_{kt}, X_{kt}, \tau_{kt})$, which can be decomposed into endogenous state variables N_{kt}, exogenous profit-shifting state variables X_{kt}, and the lease term time τ_{kt}. Investment decisions depend on N_{kt} and X_{kt} because these state variables are assumed to affect profits. Because of the finite-horizon nature of the firm's exploration investment problem, the finite-valued and exogenous lease term time τ_{kt} affects investment decisions as well, as will be explained below. In the present model, there are two endogenous state variables N_{kt}: the total number of tracts in market k that have been explored before time t, and the total number of tracts in market k that have been developed before time t. These endogenous state variables capture the strategic component of the firms' investment timing decisions. The exogenous state variables X_{kt} include the drilling cost and the oil price and are assumed to evolve as a finite state first-order Markov process: $X_{k,t+1} \overset{iid}{\sim} F_X(\cdot | X_{kt})$. In other words, the next period's value $X_{k,t+1}$ of the exogenous state variables are assumed to

be independently and identically distributed (i.i.d.) with a probability distribution that depends only on the time-t realization X_{kt} of the exogenous state variables, and not additionally on what happened before time t (Dixit & Pindyck, 1994).[6]

In addition to the publicly observable state variables Ω_{kt}, each firm's time-t investment timing decision also depends on two types of shocks that are private information to the firm and unobserved by either other firms or by the econometrician. The first source of private information is a pre-exploration shock μ_{it} to an unexplored tract i at time t. This pre-exploration shock, which is only observed by the firm owning tract i, represents any and all private information that affects the exploration investment decision made on tract i at time t. Such private information may include, for example, idiosyncratic shocks to exploration costs and the outcome of the post-sale, pre-exploration seismic study conducted on tract i at time $t-1$.[7] Following Pakes, Ostrovsky and Berry (2005), assume that the pre-exploration shock μ_{it} is an independently and identically distributed random variable with an exponential distribution and mean σ_μ. That is, $\mu_{it} \overset{iid}{\sim} exponential(\sigma_\mu)$.

The second source of private information is a pre-development shock ε_{it} to an explored but undeveloped tract i at time t. This pre-development shock, which is only observed by the firm owning tract i, represents any and all private information that affects the development investment decision made on tract i at time t. Such private information may include, for example, the outcome of the exploratory drilling conducted on tract i at time $t-1$. Following Pakes, Ostrovsky and Berry (2005), assume that the pre-development shock ε_{it} is an independently and identically distributed random variable with an exponential distribution and mean σ_ε. That is, $\varepsilon_{it} \overset{iid}{\sim} exponential(\sigma_\varepsilon)$. In addition, assume that the pre-exploration shocks μ_{it} and the pre-development shocks ε_{it} are independent of each other.[8] All distributions are common knowledge.

In the absence of strategic considerations, the firm owning tract i would base its investment timing decisions on only the exogenous state variables X_{kt}, the lease term time τ_{kt}, and the private shocks μ_{it} and ε_{it}. To derive its dynamically optimal investment policy, it would solve a single-agent dynamic programming problem.

If information and extraction externalities were present, however, then strategic considerations would become important. As a consequence, the exploration and development investment decisions of the firm owning tract i in market k would depend on the exploration and development investment decisions of the firms owning the other tracts in market k. In other words, the firm owning tract i would base its investment timing decisions not only on the exogenous state variables X_{kt}, the lease

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[6]The lease term time τ_{kt} evolves as a finite state first-order Markov process as well. Lin (2007) includes this exogenous finite-valued variable τ_{kt} as a separate argument distinct from X_{kt} both because it does not affect profits and also to elucidate my later exposition of the finite-horizon nature of the exploration stage.

[7]Firms conduct and analyze seismic studies in order to help them decide whether or not to begin exploratory drilling (John Shaw, personal communication, 18 April 2003; Bob Dye, Apache, personal communication, 21 January 2004; Jon Jeppesen, Apache, personal communication, 21 January 2004; Mark Bauer, Apache, personal communication, 21 January 2004; Billy Ebarb, Apache, personal communication, 22 January 2004).

[8]The assumptions that both types of shocks are i.i.d. and independent of each other, while restrictive, are needed in order for the estimation technique used in this paper to work. If either type of shock were serially correlated (or if, at the extreme, there were tract fixed effects), then firms would base their decisions not only on the current values of the state variables and of their shocks, but also on past values of the state variables and shocks as well. The state space would then be too large. If the distribution of the pre-development shock ε_{it} depended on the realization of the pre-exploration shock μ_{it} (e.g., the μ_{it} at the time of exploration), then μ_{it} would be a state variable in the development stage of production. As a consequence, the econometrician would need to observe μ_{it}, which she does not. The i.i.d. assumption is reasonable if the shocks are interpreted to encompass all idiosyncratic factors affecting investment decisions, including managerial shocks and technological shocks. Moreover, since one of the state variables is the average winning bid, which is a measure of tract value, it is reasonable to assume that, conditional on tract value, shocks are i.i.d.

term time τ_{kt}, and the private shocks μ_{it} and ε_{it}, but also on the endogenous state variables N_{kt} as well, namely the total number of tracts in its market k that have been explored before time t and the total number of tracts in market k that have been developed before time t. Each firm would then no longer solve merely a single-agent dynamic programming problem, but rather a multi-agent dynamic game.

The equilibrium concept used in the model is that of a Markov perfect equilibrium. Each firm is assumed to play a Markov "state-space" strategy: the past influences current play only through its effect on the state variables. A firm's dynamically optimal investment policy is then the Markov strategy that it plays in the Markov perfect equilibrium, which is a profile of Markov strategies that yields a Nash equilibrium in every proper subgame (Fudenberg & Tirole, 1998).

While each firm's time-t investment decision depends on both the publicly available endogenous and exogenous state variables Ω_{kt} as well as the firm's own private information μ_{it} or ε_{it}, its perception of its neighbor's time-t investment decisions depend only on the publicly observable state variables Ω_{kt}. This is because, owing to the above assumptions on the observable state variables and on the unobservable shocks, firms can take expectations over their neighbors' private information.[9] In equilibrium, firms' perceptions of their neighbors' investment probabilities should be consistent with those that are actually realized (Starr & Ho, 1969).

The model has at least one Markov perfect equilibrium, and each equilibrium generates a finite state Markov chain in Ω_{kt} tuples (Pakes, Ostrovsky & Berry, 2005).[10] Although model assumptions do not guarantee a unique equilibrium, they do ensure that there is only one set of equilibrium policies that is consistent with the data generating process. It is thus possible to use the data itself to pick out the equilibrium that is played. For large enough samples, the data will pick out the correct equilibrium and the estimators for the parameters in the model will be consistent (Pakes, Ostrovsky & Berry, 2005).

The firm's dynamic decision-making problem is as follows. The first-stage problem is to determine the optimal policy for investment in exploration. Because firms must begin exploration before the end of their lease term, or else relinquish their lease, this is a finite-horizon problem. As a consequence, firms' decisions will depend not only on the profit-shifting state variables N_{kt} and X_{kt}, but also on time t. However, since firms can only make exploration decisions at the beginning of periods $t = 0, ..., T - 1$, the time dependence only applies until time $t = T - 1$, after which exploration can no longer begin and the endogenous variable that counts the total number of tracts in the market that have been explored stays constant. It is for this reason that the exogenous and finite-valued state variable "lease term time" τ_{kt} captures the entire time dependence of the problem.

The second stage of the firm's dynamic decision-making problem is to determine the optimal timing for investing in the development of a tract that has already been explored. This second-stage problem has both a finite-horizon component and an infinite-horizon component. A firm's development strategy depends in part on its perceptions of the future exploration policies of the firms in the market. Since exploration policies depend on time until time $t = T - 1$, this means that perceptions, and therefore development strategies, will depend on time for $t < T$. As a consequence, the dynamic programming problem for time $t < T$ is a finite-horizon problem. However, because the lease term only applies to the exploration stage of production, and because the endogenous variable that counts the total number of tracts in the market that have been explored – a variable

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[9]While each firm plays a pure strategy, from the point of view of their neighbors, they appear to play mixed strategies. Thus, as with Harsanyi's (1973) purification theorem, a mixed distribution over actions is the result of unobserved payoff perturbations that sometimes lead firms to have a strict preference for one action, and sometimes a strict preference for another.

[10]A Markov chain is a Markov process on a finite state space (Stokey, Lucas & Prescott, 1989).

that depends on the time-dependent exploration policies of the firms in the market – stays constant after the lease term expires, the dynamic programming problem for the development stage from time T onwards is an infinite-horizon problem that does not depend on time. Thus, once again, the lease term time τ_{kt} sufficiently captures the entire time dependence of the problem.

The firm's sequential investment problem is a two-stage optimization problem, and can be solved backwards using dynamic programming (Dixit & Pindyck, 1994). In the second, or development, stage of oil production, a firm with an explored but undeveloped tract i must decide if and when to invest in a production platform. Assume that the profit $\pi^d(\Omega_{kt}, \varepsilon_{it}; \theta)$ that a firm will get after developing tract i at time t can be separated into a deterministic component and a stochastic component as follows:

$$\pi^d(\Omega_{kt}, \varepsilon_{it}; \theta) = \pi_0^d(\Omega_{kt}; \theta) + \varepsilon_{it} \ , \tag{1}$$

where the deterministic component of profit is linear in the publicly observable state variables:

$$\pi_0^d(\Omega_{kt}; \theta) \equiv N'_{kt}\gamma_N + X'_{kt}\gamma_X \ , \tag{2}$$

and where the stochastic component is the privately observed pre-development shock ε_{it}.[11] The development profit is therefore independent of time (and lease term time) except through the state variables (N_{kt}, X_{kt}) and the shock ε_{it}.

Let $\gamma \equiv (\gamma_N, \gamma_X)$ denote the vector of all the coefficients in the development profit function. The coefficients γ_N in the profit function on the endogenous state variables N_{kt} – the total number of tracts in the market that have been explored and the total number of tracts in the market that have been developed – indicate whether and how one firm's profits depend on the production decisions of its neighbors. If a neighbor explores, then the state variable counting the total number of tracts in the market that have been explored increases by one and the value of the development profits increase by the value of its coefficient. Similarly, if a neighbor develops, then the state variable counting the total number of tracts in the market that have been developed increases by one and the value of the development profits increase by the value of its coefficient. The coefficients γ_N on the endogenous variables thus measure the net effects of the information and extraction externalities, and therefore indicate whether firms interact strategically on net. Positive values of the coefficients γ_N would indicate that the information and extraction externalities were positive on net, and therefore that the information externality was dominant. Negative values would indicate that the externalities were negative on net, and therefore that the extraction externality was dominant.

The value V^e of an explored but undeveloped tract i in market k at time t is given by:

$$V^e(\Omega_{kt}, \varepsilon_{it}; \theta) = \max\{\pi^d(\Omega_{kt}, \varepsilon_{it}; \theta), \beta V^{ce}(\Omega_{kt}; \theta)\}, \tag{3}$$

where $\beta \in (0, 1)$ is the discount factor and $V^{ce}(\Omega_{kt}; \theta)$ is the continuation value to waiting instead of developing at time t. For the structural estimation, Lin (2007) sets the discount factor β to 0.9. The continuation value to waiting is the expectation over the state variables and shocks of next period's value function, conditional on not developing this period:

$$V^{ce}(\Omega_{kt}; \theta) = E\left[V^e(\Omega_{k,t+1}, \varepsilon_{i,t+1}; \theta)|\Omega_{kt}, I_{it}^d = 0\right], \tag{4}$$

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[11]If there were additional market state variables that affected profits but were unobserved by the econometrician, then $\pi^d(\Omega_{kt}, \varepsilon_{it}; \theta)$ can be interpreted as the expected profits conditional on the available information Ω_{kt} (Pakes, Ostrovsky & Berry, 2005). Under this interpretation, spatially correlated unobservables do not pose a concern.

where I_{it}^d is an indicator for whether development began on tract i at time t.

Let $g^d(\Omega_{kt}; \theta)$ denote the probability of developing an explored but undeveloped tract i at time t conditional on the publicly available information Ω_{kt} on time t, but not on the private information ε_{it}. The development probability $g^d(\Omega_{kt}; \theta)$ function represents a firm's perceptions of the probability that a neighbor owning an explored but undeveloped tract will decide to develop its tract in period t, given that the state of their market at time t is Ω_{kt}. Moreover, a firm's expectation of its own probability of development in the next period is simply the expected value of the next period's development probability, conditional on this period's state variables: $E[g^d(\Omega_{k,t+1}; \theta)|\Omega_{kt}]$.

Using the exponential distribution for ε_{it} and equation (1) for development profits as shown in Lin (2007), the continuation value $V^{ce}(\cdot)$ can be reduced to:

$$V^{ce}(\Omega_{kt}; \theta) = E[\beta V^{ce}(\Omega_{k,t+1}; \theta) + \sigma_\varepsilon g^d(\Omega_{k,t+1}; \theta)|\Omega_{kt}, I_{it}^d = 0], \tag{5}$$

and the development probability $g^d(\cdot)$ can be reduced to the following function of the continuation value, the state variables and the parameters:

$$g^d(\Omega_{kt}; \theta) = \exp\left(-\frac{\beta V^{ce}(\Omega_{kt}; \theta) - \pi_0^d(\Omega_{kt}; \theta)}{\sigma_\varepsilon}\right). \tag{6}$$

In the first, or exploration, stage of oil production, a firm with an unexplored tract i must decide if and when to invest in exploratory drilling. Owing to the sequential nature of the investments, the publicly observable deterministic component of the payoff $\pi_0^e(\cdot)$ to exploring in the first stage is equal to the expected value of having an explored but undeveloped tract in the second stage, net the cost of exploration $c^e(\cdot)$:

$$\pi_0^e(\Omega_{kt}; \theta) \equiv E_\varepsilon\left[V^e(\Omega_{kt}, \varepsilon_{it}; \theta)|\Omega_{kt}\right] - c^e(\Omega_{kt}; \theta), \tag{7}$$

where the exploration cost is assumed to be linear in the exogenous cost-shifting state variables:[12]

$$c^e(\Omega_{kt}; \theta) = -X'_{kt}\alpha. \tag{8}$$

Assume that the actual payoff $\pi^e(\cdot)$ to exploring tract i at time t also includes a privately observed stochastic component as well:

$$\pi^e(\Omega_{kt}, \mu_{it}; \theta) = \pi_0^e(\Omega_{kt}; \theta) + \mu_{it}, \tag{9}$$

where the stochastic component is the pre-exploration shock μ_{it}.

The value V^n of an unexplored tract i in market k and time t is given by:

$$V^n(\Omega_{kt}, \mu_{it}; \theta) = \max\{\pi^e(\Omega_{kt}, \mu_{it}; \theta), \beta V^{cn}(\Omega_{kt}; \theta)\}, \tag{10}$$

where $V^{cn}(\Omega_{kt}; \theta)$ is the continuation value to waiting instead of exploring at time t. The continuation value to waiting is the expectation over the state variables and shocks of next period's value function, conditional on not exploring this period:

$$V^{cn}(\Omega_{kt}; \theta) = E\left[V^n(\Omega_{k,t+1}, \mu_{i,t+1}; \theta)|\Omega_{kt}, I_{it}^e = 0\right], \tag{11}$$

where I_{it}^e is an indicator for whether exploration began on tract i at time t. The lease term imposes the following boundary condition:

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[12]I define costs with a negative sign so that the coefficients can be interpreted as coefficients in the exploration profit function. Variables that increase cost will decrease profit, and vice versa.

$$V^n\left((N,X,T),\mu;\theta\right) = 0 \quad \forall N,X,\mu \ . \tag{12}$$

Let $g^e(\Omega_{kt};\theta)$ denote the probability of exploring an unexplored tract i at time t conditional on the publicly available information Ω_{kt} on time t, but not on the private information μ_{it}. As with the development probability, the current value of the exploration probability represents a firm's perceptions of the probability that a neighbor owning an unexplored tract will decide to explore its tract in period t, given that the state of their market at time t is Ω_{kt}; its expected value at time $t+1$ represents a firm's expectation of its own probability of exploration in the next period.

Using the exponential distribution for μ_{it} and equation (9) for exploration profits as shown in Lin (2007), the continuation value $V^{cn}(\cdot)$ to waiting instead of exploring can be reduced to:

$$V^{cn}(\Omega_{kt};\theta) = E\left[\beta V^{cn}(\Omega_{k,t+1};\theta) + \sigma_\mu g^e(\Omega_{k,t+1};\theta)|\Omega_{kt}, I^e_{it} = 0\right], \tag{13}$$

and the exploration policy function $g^e(\cdot)$ can be reduced to the following function of the continuation values, state variables and parameters:

$$g^e(\Omega_{kt};\theta) = \exp\left(-\frac{\beta V^{cn}(\Omega_{kt};\theta) - \left(\beta V^{ce}(\Omega_{kt};\theta) + \sigma_\varepsilon g^d(\Omega_{kt};\theta)\right) + c^e(\Omega_{kt};\theta)}{\sigma_u}\right). \tag{14}$$

Owing to the sequential nature of the investment decisions, the continuation value $V^{ce}(\cdot)$ and the investment probability $g^d(\cdot)$ from the development stage appear in the expression for the investment probability $g^e(\cdot)$ in the exploration stage.

The ex ante expected value of an unexplored tract at time $t=0$, where expectations are taken over the pre-exploration shock μ, is given by:

$$E_\mu\left[V^n(\Omega_{k0},\mu_{i0};\theta)|\Omega_{k0}\right] = \beta V^{cn}(\Omega_{k0};\theta) + \sigma_\mu g^e(\Omega_{k0};\theta). \tag{15}$$

2.3   Structural econometric estimation

Since 1954, the U.S. government has leased tracts from its federal lands in the Gulf of Mexico to firms interested in offshore petroleum production by means of a succession of lease sales. A lease sale is initiated when the government announces that an area is available for exploration, and nominations are invited from firms as to which tracts should be offered for sale. In a typical lease sale, over a hundred tracts are sold simultaneously in separate first-price, sealed-bid auctions. Many more tracts are nominated than are sold, and the nomination process probably conveys little or no information (Porter, 1995). A tract is typically a block of 5000 acres or 5760 acres (Marshall Rose, Minerals Management Service, personal communication, 9 November 2005). The size of a tract is often less than the acreage required to ensure exclusive ownership of any deposits that may be present (Hendricks & Kovenock, 1989), and tracts within the same area may be located over a common pool (Hendricks & Porter, 1993). To date, the largest petroleum field spanned 23 tracts. Depending on water depth, 57-67 percent of the fields spanned more than one tract and 70-79 percent spanned three or fewer tracts (Marshall Rose, Minerals Management Service, personal communication, 31 March 2005). Because neighboring tracts of land may share a common pool of petroleum reserve, information and extraction externalities that lead firms to interact strategically may be present. As a consequence, petroleum production on the federal leases may be inefficient.

To estimate the parameters of the model of the investment timing game in the Gulf of Mexico, the econometric estimation technique used employs a two-step semi-parametric estimation procedure. It is an extension of the estimator proposed by Pakes, Ostrovsky and Berry (2005) to finite-horizon, multi-stage games. In the first step, the continuation values are estimated non-parametrically and these estimates are used to compute the predicted probabilities of exploration and development. In the second step, the parameters $\theta \equiv (\sigma_\mu, \sigma_\varepsilon, \gamma, \alpha)'$ are estimated by matching the predicted probabilities with the actual probabilities in the data via Generalized Method of Moments (GMM). Standard errors are formed by a parametric bootstrap. Details about the estimation are in Lin (2007). The model is applied to data on wildcat tracts offshore of Louisiana and Texas that were auctioned in federal lease sales between 1954 and 1979, inclusive.

The results from the structural econometric model do not indicate that externalities from exploration have any net strategic effect. A firm's profits from development does not depend significantly on the exploration decisions of its neighbor. In contrast, externalities from development do have a net strategic effect. A firm's real profits from developing increase when its neighbor develops, perhaps because this is a signal to the firm that the neighbor's exploratory efforts were successful, and therefore that there may be deposits present.

There are several possible explanations why the results reject strategic, non-cooperative behavior during exploration. One is that the tract sizes are large enough that cross-tract externalities are insignificant or even nonexistent. A second is that cross-tract externalities exist, but firms owning neighboring tracts cooperate to jointly internalize the inefficient externalities they impose on each other, for example by forming joint ventures in exploration[13] or by consolidating their production rights through purchase or unitization.[14] A third is that cross-tract externalities are significant, but the positive information externality exactly cancels the negative extraction externality, resulting in zero net strategic effects.

To distinguish among these three explanations for the lack of strategic interactions during exploration, Lin (2007) estimates the strategic interactions by tract size. If externalities are insignificant when tracts are large enough, then one would expect to see strategic, non-cooperative behavior only on small tracts. This is because the smaller the tract size, the more likely the tracts are located over a common pool, and therefore the more acute the information and extraction externalities faced by the firms. Evidence for significant strategic interactions on small tracts but not on large tracts would thus be consistent with the first explanation.

If externalities exist even for the largest tracts in the sample, but are eliminated through coordination, then, assuming firms would coordinate regardless of tract size, one would not expect to see any strategic, non-cooperative behavior even on small tracts. Insignificant strategic interactions

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[13]Joint ventures in exploration occur less frequently than one might expect, however, because negotiations are contentious, because firms fear allegations of pre-sale anti-trust violations (Marshall Rose, Minerals Management Service, personal communication, 3 May 2005), and because prospective partners have an incentive to free ride on a firm's information gathering expenditures (Hendricks and Porter, 1992). In their theoretical model of the persuasion game, Hendricks and Kovenock (1989) find that, even with well-defined property rights, bargaining does not eliminate all the inefficiencies of decentralized drilling decisions. As a consequence, the information externality may not be fully internalized.

[14]Under a unitization agreement, a single firm is designated as the unit operator to develop the entire reservoir, while the other firms share in the profits according to negotiated formulas (Libecap & Smith, 1999b). There are many obstacles to consolidation, however, including contentious negotiations, the need to determine relative or absolute tract values, information costs, and oil migration problems (Libecap & Wiggins, 1984). In addition, another free rider problem that impedes coordination is that firms may fear that if they reveal to other firms their information or expertise, for example about how to interpret seismic data, then they may lose their advantage in future auctions (Hendricks & Porter, 1996). Thus, despite various means of coordination, firms may still behave strategically and non-cooperatively, and information and extraction externalities may not be fully internalized.

regardless of tract size would thus be consistent with the second explanation.[15]

If strategic interactions do not occur on net because the positive information externality exactly cancels the negative extraction externality, then one may not expect the exact cancellation to still take place when the tract size is small. This is because the geographical span of the information externality is larger than that of the extraction externality: while the former only requires that tracts may share common geological features, the latter requires that tracts may be located over a common pool. As a consequence, it is possible for the information externality to be present on all the tracts in the sample, but for the extraction externality to be present on only the smaller tracts. Theory therefore suggests that the importance of the extraction externality relative to the information externality should be greater on small tracts than on large tracts. Thus, if the externalities cancel when all the tract sizes are considered, one might expect that the negative extraction externality would dominate the positive information externality when the sample is limited to small tracts only. Strategic interactions that are more significantly negative on small tracts than on large tracts would therefore be consistent with the third explanation.

According to the structural estimation, the importance of strategic interactions depends on tract size. As expected, strategic interactions are more likely to take place on smaller tracts, where the externalities are more acute. When the tract size is large enough, the net strategic effects of the externalities from both exploration and development disappear. Also as predicted by theory, the relative importance of the extraction externality from exploration with respect to the information externality is greater on small tracts than on large tracts; on large tracts, the two externalities cancel each other out.

The results suggest that, by selling predominantly large tracts, the federal government has minimized inefficiencies in petroleum production that may have resulted from non-cooperative strategic interactions.

3 Alaska

3.1 Background

Though both are important regions for U.S. petroleum production, Alaska differs from the Gulf of Mexico in several ways. Alaska's oil production occurs on land in an arctic environment while the Gulf of Mexico oil production is offshore in a tropical environment. There are few oil producers in Alaska but many in the Gulf of Mexico. Alaska oil is delivered to market via 800 miles of pipeline and approximately 3,000 miles of tanker travel while Gulf of Mexico oil is delivered directly to refineries in the gulf coast states (Alyeska Pipeline Service Company, 2007a; Kumins, 2005).

The oil and gas industry in the state of Alaska presents a unique "laboratory" for the study of primary energy production with structural econometric methods for several reasons. The state is isolated, with only one export point for oil (Valdez) and only one pipeline for transporting oil the 800 miles from the primary area of production (the North Slope) to Valdez. As such, the physical boundaries of the market are well defined. The history of oil production in Alaska runs from the late 1950s to the present; this relatively recent history combined with good record keeping in Alaska suggests the presence of the quantity and quality of data necessary for structural econometric

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[15]It is also possible that the coefficients that arise when firms coordinate are significant, but are different from those that would arise under the non-cooperative outcome.

modeling. Furthermore, the history of oil production in Alaska includes clear demarcation by structural breaks into three distinct periods:[16]

• 1957 to 1977 was a period of oil discovery, exploration, and limited development that occurred before completion of the 800-mile Trans-Alaska Pipeline (TAPS) connecting the North Slope oil fields to the port of Valdez, and that occurred under Alaska's initial tax laws, including the corporate income tax, property tax, royalty, and severance tax;

• 1977 to 2006 was a period of oil production after revision of Alaska's severance tax system to include the "Economic Limit Factor," a revision intended to spur new exploration and development investment;[17] and

• 1987 to 2006 was a period of oil production after significant revision of Alaska's corporate income tax.

These "game changing" structural breaks afford the opportunity to evaluate the impact of changing conditions – especially the construction of infrastructure for delivering oil to market and several changes to the tax landscape – on producer investment decisions, and provide valuable reference points for modeling strategic behavior. The outcome of such analysis is particularly relevant for Alaska in the near future, as it passed an entirely new severance tax system in 2006 and is currently contemplating construction of a $25 billion, 3,000-mile natural gas pipeline to bring 35 trillion cubic feet of known natural gas reserves on the North Slope to market (USGS, 2005; Petroleum Production Tax website, 2007; Alaska Gas Pipeline website, 2007). Finally, the composition of firms active in oil exploration and development in Alaska has changed over time, leading to the present situation of only three primary oil producers active in the state: BP, ConocoPhillips, and ExxonMobil. The small number of players presents a situation where economic theory would suggest the possibility of strong strategic considerations and the potential for collusive actions. The questions of whether strategic considerations and collusion are important in Alaska are important to policy makers in the state and are questions we can investigate with structural econometric modeling.

Study of Alaska's oil production industry is particularly valuable now, because of Alaska's potential role in the next few decades of U.S. energy supply. Natural gas is often cited as the clean energy source for future energy systems, including the nascent hydrogen fuel system.[18] As climate change becomes a more significant motivation in energy decisions, demand for low-carbon natural gas will grow. Thus, understanding future natural gas supply in the United States is relevant to a wide range of future scenarios, from business as usual to hydrogen-fueled vehicles. Alaska has been projected to provide 6.5 percent of United States supply for the period 2016 to 2030.[19] But infrastructure for delivering this gas to market has not been built for a variety of reasons, including strategic considerations (Leighty, 2007). Similarly, the potential for additional

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[16] The first oil leases were sold in the Cook Inlet area near Anchorage in 1959. But the discovery of the Prudhoe Bay oil field on Alaska's North Slope in 1968 signaled the start of what we now consider Alaska's oil and gas industry. The Prudhoe Bay field contained over 20 billion barrels when discovered, making it more than double the size of the next largest oil field in the United States, the East Texas oil field (Vincent Sean Monico, BP Exploration Alaska, personal communication, 2 July 2007). Completion of the Trans-Alaska pipeline in 1977 created a means for delivering this oil to market; the pipe saw peak flow of 2 million barrels per day in 1988 and currently carries just under 1 million barrels per day (Alyeska Pipeline Service Company, 2007b).

[17] The petroleum production tax (PPT), passed in 2006, replaced the gross-profits-based ELF system with a net-profits-tax, thereby creating another structural break and defining the start of a new period in Alaska's oil industry (Petroleum Production Tax website, 2007; Alaska Department of Revenue website, 2007; Alaska State Legislature website, 2007).

[18] Ongoing research suggests on-site reformation of natural gas will be the low cost hydrogen production method for vehicle fuel until significant market penetration (perhaps 10 percent) of hydrogen vehicles is achieved (Personal Communication, Nils Johnson, presentation in STEPS seminar at UC Davis, 2007).

[19] State of Alaska, http://www.gov.state.ak.us/gasline/, accessed 27 March 2007.

oil exploration and development in Alaska (e.g. in the Arctic National Wildlife Refuge, ANWR) will likely be a perennial topic of interest as oil becomes more scarce, and will require development of new institutional and regulatory frameworks. Study of the effects of these institutions and policies to find what policy parameters lead to socially desirable outcomes is especially important in the case of Alaska since we are now (potentially) designing the new institutions and policies for ANWR development and a $25 billion, 3,000-mile natural gas pipeline. By analyzing strategic behavior under existing policies and institutions, we can improve national energy planning and policy for the future, from fossil energy supplies to early development of and transition to alternative fuel systems (e.g., hydrogen).

The research we are conducting focuses on the effects of institutions (e.g., government policy and regulation) on strategic firm behavior and other sources of inefficiencies in energy markets, with the goal of finding what policy parameters lead to socially desirable outcomes. We seek a holistic understanding of Alaska's oil industry by employing several dynamic structural econometric modeling techniques with real-world data to evaluate ongoing firm decisions.

3.2   The multi-stage investment timing game

Firms producing petroleum in Alaska make the following decisions: (1) whether to bid on a lease; (2) whether to invest in a seismic study of a particular area; (3) whether to apply for exploratory (or any) well drilling; (4) whether to proceed with exploratory well drilling; (5) whether to initiate, participate in and/or complete a unit agreement; (6) whether to invest in infill drilling in a producing unit to maintain or boost production; (7) whether to invest in production infrastructure; (8) whether to invest in major infrastructure such as the TAPS, a gas treatment facility, or collector pipes; and (9) production quantities.

The firms' production decisions are dynamic because the current period decisions will impact next period profits. The classic example in the oil industry is the fact that a production decision today impacts the reserves quantity tomorrow. Additionally, exploration investment decisions made today will also impact the reserves quantity tomorrow through new finds. Also, the sequential investment decisions necessary prior to production will impact the ability to produce in the next period. The sequential nature of investments causes the situation to be dynamic, making it a multi-stage game. That is, for example, unitization must come before production in Alaska, so the decisions leading up to unitization are one stage and productions decisions after unitization are a second stage.

There are several sources of strategic behavior in Alaska. In the leasing process, the game is a closed-bid auction, where each company uses its private information (and public information) to assess the value of lease tracts and determine their bids. Each company's optimal bid will be the lowest possible such that it is larger than all other bids (but still lower than their valuation of the tract). Thus, the bidding is a game with each player's strategy contingent on the play of the others.

In the exploration phase after leasing, each company proceeds with the knowledge that a unit agreement must be negotiated before production. Thus, the goal of exploration is both to find oil and to document a large share of that oil under the leases a particular company owns. Since exploration is costly, there is an optimal amount of exploration that is related to the amount that other companies do. On the one hand, a company would save money by letting other companies explore to find the oil and then getting a share during the unit negotiations. But, the unit negotiation will require enough information to credibly argue for a large share of the production. This could be accomplished by having good geologists to review the information provided from the other companies' exploratory activities and/or independent exploration by the particular company

in question. In addition, there is the question of whether other companies will do exploration quickly enough and in the locations most advantageous to the company in question. Thus, it would seem that the companies most intent on finding new resources due to their firm-specific business model would do more exploration rather than wait for others whereas the companies least intent on finding new resources would do less exploration. Similarly, it would seem that companies with large tracts of leases and/or no nearby leases would be more prone to invest in exploration (since no one else is going to find the oil under their leases) than in cases with mixed lease ownership all in close proximity.

3.3 A dynamic model of unit production

The previous work by Lin (2007) documented the potential impact of government leasing policy on multi-stage investment timing decisions in oil exploration and development in the Gulf of Mexico. The focus in her work was on the potential for lease tract size, set by government leasing policy, to induce wasteful non-cooperative strategic behavior due to competing information and extraction externalities. The modeling we are developing for the Alaska oil industry is different in methodology and specific research questions, but addresses the same fundamental question of whether government policy creates inefficiency in the oil industry.

Like the previous work by Lin (2007), the proposed model of Alaska infill drilling and unit production decisions will incorporate the impact of government policy on the dynamic optimum control problem inherent in these decisions. However, unlike the research by Lin (2007), this model focuses on oil production decisions rather than exploration and development investments, and develops a model of the optimal production path to which actual production decisions can be compared. Consequently, the model does not include strategic considerations (e.g., information and extraction externalities) since each unit operator is treated as independent, and does not include exploration investment decisions since the model begins after unitization. However, the model does offer the ability to estimate the optimal oil production path, how that path may change under different government tax policies and unit contract structures, whether individual producers have characteristic "corporate philosophies" reflected in their unit management decisions, and to evaluate how closely Alaskan oil producers have approximated the optimal rate of production. Our model will also enable us to evaluate if tax and leasing policies and contract structures introduced inefficiencies in petroleum production, and to design policies and institutions that lead to more socially efficient and desirable outcomes.

Our research seeks to improve our understanding of the investment and production timing decisions in oil supply industries and of the potential impact government policy may have on these decisions. This knowledge presents the opportunity to avoid inefficiency caused by non-cooperative strategic behavior and sub-optimal production paths.

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