The Equilibrium of a Real Options Bargaining and Exercise Game — Evidence from the Natural Gas Industry

Yuanshun Li
Ted Rogers School of Business, Ryerson University

Gordon Sick
Haskayne School of Business, University of Calgary

March 9, 2010

Abstract

This paper empirically examines the equilibrium of firms investment decision given a context in which firms output price and production volume are uncertain, firms may choose to invest cooperatively or competitively, and there are economies of scale (network effects). In this setting, interacting firms play a real option bargaining and exercise game under incomplete information. The results from duration analysis show that output commodity prices have a negative effect on the duration of investment lag and the network effect has an positive effect on the duration of investment lag. In addition, the logit model results show that the real option exercise price has a negative effect on the probability of cooperation, and the network effect has a positive effect on the probability of cooperation.

1 Introduction

Firms' optimal investment decisions under uncertainty has been a controversial topic for a long time due to the observed deviation from zero NPV threshold. The standard real options literature, including Brennan and Schwartz (1985); Dixit and Pindyck (1994); Dixit (1995); Capozza and Sick (1991); Sick (1995); Trigeorgis (1996), asserts that investments should be delayed until uncertainty is resolved or wait for the optimal threshold. However, the competitive real options literature, including Fudenberg and Tirole (1985); Grenadier (1996, 2002); Mason and Weeds (2005); Garlappi (2001); Boyer et al. (2001); Murto and Keppo (2002); Lambrecht and Perraudin (2003); Huisman and Kort (2004); Thijssen et al. (2006); Smit and Trigeorgis (2004), argues that competition diminishes the real option values and mitigates investment delays, thus, with sufficient competition, firms' investment threshold may be pushed back to zero net present value (NPV). The recent article, Novy-Marx (2007) shows that opportunity costs and supply side heterogeneity reduce the competition effect and leads to an investment threshold even later than the standard real option threshold.

Empirical work in testing the competitive real option theory is rare probably due to the shortage of firms' capital budgeting data in irreversible investment at a project level . In a non-competitive setting, Favero et al. (1994) develop and test a duration model to explain the appraisal development lag for investment in oil fields. Hurn and Wright (1994) use a discrete time hazard regression models to analyze the appraisal lag and the production start-up lag using North Sea Oil Data. Bulan (2005) test the real options behavior in capital budgeting decisions using a firm-level panel data set of U.S. companies in the manufacturing sector by looking at the relationship between the firm's investment to capital ratio and total firm uncertainty, measured as the volatility of the firm's equity returns. They find that increased industry uncertainty negatively affects firm investment, and increased firm-specific uncertainty also depresses firm investment. Bulan et al. (2002) examine condominium developments in Vancouver in an competitive setting. They find that risk increase leads to delay of new real estate investments, and increases in competition negates the negative effect of risk on investments. All these previous empirical results support that (1) Uncertainty defers the investment because firms want to keep the real option value; (2) Competition accelerates the investment because it erodes option values.

This chapter tests whether firms will consider the possibility of cooperating with their competitors when the competition becomes too fierce using the project level data from Alberta natural gas exploration and processing industry. As discussed in Sick and Li (2007), in industries with economies of scale or network effects, firms may benefit from cooperation by avoiding the erosion effect of competition on real option value.

2 The Data

2.1 Industry background

The development of a natural gas field can be a long-term process. First, in the exploration stage, firms need to collect geological survey data, seismic data and gravitational data in order to examine the surface structure of the earth, and determine the possible locations of gas reservoir. Second, in the drilling stage, firms need to drill several discovery wells to determine the approximate depth and quantity of the gas reservoir. If the discovery wells find that the underground gas reserve is large enough to merit the production, then firms officially have a real option to invest. To start the production, firms need to drill more production wells in order to extract gas from underground reservoir at an optimal scale. Depending on the natural gas commodity price and the estimated reserve quantity, firms may or may not wait for years before they start the actual production. This waiting period between the registration dates of discovery well and the production well is defined as the investment lag.

Raw gas needs to be processed in a gas processing plant before it can be sold in the market. The natural gas sold in the market consists mainly of methane. The raw gas extracted from the production wells is a mixture of methane and other heavier hydrocarbons - such as ethane, propane, butane and pentane - as well as water vapour, hydrogen sulphide,[1] carbon dioxide,

[1] As described by the Energy Resources Conservation Board (ERCB), an independent

nitrogen and other gases. If the natural gas at the wellhead contains more than 1% of hydrogen sulphide, it is called sour gas and has to be processed at sour gas recovery plants to extract sulphur for sale to fertilizer manufacturers and other industries. According to the Energy Resources Conservation Board (ERCB), about 30% of Canada's total natural gas production is sour, most of it found in Alberta and northeast British Columbia. The average rate of sulphur recovery rate at Alberta's sulphur recovery plants has improved from 97.5% in 1980 to 98.8% in 2000. Because of the potential environment issues of H_2S, the construction and production of sour gas plants is stringently regulated by the ERCB.

Different types of gas plants may engage in different processes, and their construction costs and operating costs may vary in a wide range. Once the raw gas reaches the surface at the production wellhead, it is transported through the gathering systems from individual wells to centralized processing plants, where most non-methane substances are to be removed from the gas stream. A gas processing plant may undertake four main general processes which include oil and condensate removal, water removal, separation of natural gas liquids (NGLs) and sulfur and carbon dioxide removal. In

---

quasi-judicial agency of the Government of Alberta, Canada regulating Alberta's provincial energy industries such as oil, natural gas, oil sands, coal, and pipelines, hydrogen sulphide (H_2S) is a colourless substance that is poisonous to humans and animals. Also known as hydrosulfuric acid, sewer gas, and stink damp, it is recognizable by its rotten egg smell at very low concentrations (0.01 - 0.3 parts per million). Exposure at higher concentrations of H_2S affects a person's sense of smell and, as a result, there is no perceptible odor. Exposure to high concentrations of H_2S (150 - 750 parts per million) can cause a loss of consciousness and possible death.

Alberta, the ERCB categorizes those centralized processing plants into four types, sweet gas plant, acid gas flaring gas plant, acid gas injection gas plant and sulphur recovery gas plant. The actual processes taking place in these four types gas plants include absorption, adsorption, carbon dioxide removal, refrigeration, Turbo expander, and the Claus process to recover sulfur. After all the processes done at these centralized processing plants, the natural gas is transported to the NGL fractionation plants where the mixed stream of different natural gas liquids are separated out[2] and then to the mainline straddle plants located on major pipeline systems. To avoid unnecessary heterogeneity in gas plants, only those four types of centralized processing plants are included in the sample.

Natural gas fields are also differ by the type, depth, age and location of the underground deposit and the geology of the area. Normally, natural gas is extracted from pure gas wells and from condensate wells where there is little or no crude oil. Such gas is called non-associated gas. Sometimes, natural gas are also found in oil wells where it could be either separate from, or dissolved in the crude oil in the underground formation. These gas are called associated gas. To avoid the potential heterogeneity problem in the gas field reservoirs, only those non-associated gas fields are included in the sample.

[2]The NGLs are sold separately for use as diluent in heavy oil processing, and as feedstock for petrochemical plants or as fuel.

2.2 The variables

To empirically test the real option exercise game model, I collected data for more than $1,100$ natural gas fields and $1,200$ natural gas processing plants located in the province of Alberta. The data are from various ERCB annual publications and the registration files of individual gas processing plant and natural gas field.[3]

The discovery time starts from year 1904 and ends at year 2006. It is indicated by the registration year of the earliest discovery well within each field. ST98 report provides the name, code, location and initial established reserves for every field. It also provides the discovery year of wells and mean formation depth for all reserve pools within every field. Pool level data are grouped and summarized to form the field level data including the initial reserve, discovery year and average depth. The total number of discovery wells within every fields is calculated from ST98 too.

The production startup time extends from year 1954 to 2007 as indicated by the registration year of the earliest registered gas processing plant of each field. ST102 lists the facility ID, location, subtype code for all active and inactive natural gas production facilities. By choosing subtype 401, 402, 403, 404 and 405, four types of centralized processing plants — sweet gas plant, acid gas flaring gas plant, acid gas injection gas plant and sulphur recovery gas plant are included in the sample. ST50 reports the plant ID and location, plant operator name and code, plant licensee, plant process, registered plant

[3] A citation list of these various publications is available upon request.

capacity, registration year, ERCB approval code, fields and pools that are registered to serve. ST50 are used in conjunction with ST102 to determine the plant capacity, production startup time, and to build up the association between the plants and the fields. ST50 are record in excel file since 1999, but all previous years ST50 are recoded in the microfiche collection. In order to find the association between the plants and fields, I have to manually search through the historical ST50 in order to find the earliest plant that were registered to process gas from particular field.

The historical natural gas price from 1922 to 2007 is collected from Energy Information Administration of U.S. government. Once the field discovery time and production startup time are determined, the price at discovery and price at production are then determined by matching the year variable. Ultimately, a sample of around 500 observations was formed at the investment project level where each observation associates one plant with one fields, or several fields sometimes.

A cooperative gas processing plant is defined as one plant serving, or historically having served multiple natural gas reservoir fields that are operated by multiple field operators. A non-cooperative gas processing plant is a plant serving one field or multiple fields operated by one field operator, or historically never served multiple fields operated by multiple field operators. The variable, COOP, indicates whether the gas processing plant is cooperative. If a plant is registered to process gas from multiple fields, it is a cooperative plant and COOP is equal to one. Otherwise, it is a non-cooperative plant and COOP has a value of zero. The explanatory variables are listed in this vector,

$$\{\text{PRICEDIS}, \text{PRICEPROD}, \text{RESERVE}, \text{WELLSDISC},$$
$$\text{DURATION}, \text{DEPTH}, \text{CAPACITY}\}.$$

PRICEDIS is the natural gas price at the discovery time.

PRICEPROD is the natural gas price at the time of production.

RESERVE is the initial reserve quantity of the field.

DEPTH is the average depth of all production wells within particular field, representing the drilling costs.

CAPACITY is the plant's daily processing capacity, proxying the construction cost of the plant.

DURATION measures the investment lag between discovery time and production time.

WELLSDISC is the total number discovery wells within a certain field, representing the level of network effect. More discovery wells suggest more reserves and greater future production flows. These greater production flows would need a larger pipeline throughput volume which generates a higher level of the network effect. This variable can also be viewed as an approximate proxy of competition level. If one field has more discovery wells drilled, it is likely that they are owned by more firms which all have the potentials and motivations to become the first mover.

The main feature of the data and variables are summarized in Table 1. Out of 513 gas fields, 393 of them have been developed and producing gas as of year 2007. The mean of the variable COOP is 0.61, greater than 0.5, suggesting that more cooperative plants have been built since 1950s. The average of start production price (PRICEPROD) is more than three times higher than the price at discovery (PRICEDIS). The average investment lag is around 31 years. This indicates that on average, firms did wait for higher real option exercise price to start their production. The average depth of these production wells is $1,356$ MKB (Meters below Kelly Bushing). The average plant capacity is $1,182$ thousand cubic meters per day. The average gas reserve size is $11,268$ million cubic meters. The network effect or the competition effect (WELLSDISC) varies from one well per field to $1,068$ wells per field with an average of 105 wells per field.

3 The Empirical Models and Results

3.1 The logit model of cooperative investment

To analyze firms' strategic real option investment decision under competition, a logit model is appropriate to test whether firms may consider the option of

Variable	Obs	Mean	Std Dev.	Min	Max
coop	393	0.61	0.49	0.00	1.00
pricedis	442	0.48	0.78	0.05	7.33
priceprod	393	1.85	1.54	0.10	7.33
reserve	513	11267.93	19914.34	1.00	77780.00
wellsdisc	513	104.94	179.39	1.00	1068.00
duration	513	31.35	25.39	0.00	103.00
depth	511	1356.32	804.83	244.81	4187.00
capacity	387	1181.97	2156.66	11.90	11941.00

Table 1: **Summary Statistics.** The variable, COOP indicates whether the gas processing plant is cooperative. PRICEDIS is the natural gas price at the discovery time. PRICEPROD is the natural gas price at the time of production. RESERVE is the initial reserve quantity of the field. DEPTH is the average depth of all production wells within particular field, representing the drilling costs. CAPACITY is the plant's daily processing capacity, proxying the construction cost of the plant. WELLSDISC is the total number discovery wells within certain field, representing the level of network effect. DURATION measures the waiting period (investment lag) between discovery year and start production year.

cooperating with their competitors when facing severe competition, or simply be forced to invest as soon as NPV equals zero. The decision of cooperation is the result of a sequential bargaining game as discussed in Sick and Li (2007). If firms decide to cooperate, they build a cooperative gas plant with larger capacity to process gas from multiple fields. If firms were not able to agree on the lease rate (gas processing fee), the leader would start the investment and production along, the follower would wait until its own threshold reaches.

Specifically, Sick and Li (2007) predicts the following:

1. Firms' reservation lease rates are concave in the commodity price (for both the leader and the follower), and the size of the equilibrium cooperation range is decreasing in commodity price once the real option

to invest is exercised.

2. Firms' reservation lease rates are not very sensitive to the initial reserve level within the non-exercising region. However, they decrease as initial reserve quantity increases, and the size of the equilibrium cooperation range is decreasing in commodity price within the exercising region.

3. Within the exercising region, a larger network effect decreases the leader's and the follower's reservation lease rate. Thus, as network effect increases, the leader's minimum acceptable lease rate is lower lease rate but the follower's maximum acceptable lease rate is also reduced. Therefore, the effect of network effect on equilibrium range is mixed.

These predictions yield three testable implications for the logit model of cooperation.

Hypothesis 1 The gas price has a non-monotonic effect on the probability of cooperation. It increases the cooperation probability within the non-exercising region, which is unobservable in the data sample. All the investment projects registered in ERCB have already been exercised, so they do appear in the data. As a result of this, increased gas prices are expected to have a negative effect on the cooperation probability within the exercising region.

Hypothesis 2 Initial reserve quantity is expected to have a negative effect on the probability of cooperation within the exercising region.

Hypothesis 3 The effect of network effect or competition effect on the probability of cooperation is mixed. If the competition effect dominates the network effect (economies of scale), firms are more likely to build non-cooperative plant. If the network effect dominates the competition effect, firms are more likely to build cooperative plant.

The logit regression equation is presented as the log of the odds ratio in favor of cooperation — the ratio of the probability that firms act cooperatively to the probability that firms act non-cooperatively:

$$\begin{aligned}
\ln\left(\frac{P}{1-P}\right) &= \alpha + \beta^{\mathrm{pd}}\mathrm{PRICEDIS} + \beta^{\mathrm{pp}}\mathrm{PRICEPROD} + \beta^{\mathrm{rs}}\mathrm{RESERVE} \\
&\quad + \beta^{\mathrm{d}}\mathrm{DEPTH} + \beta^{\mathrm{c}}\mathrm{CAPACITY} + \beta^{\mathrm{w}}\mathrm{WELLSDISC} \\
&\quad + \beta^{\mathrm{dn}}\mathrm{DURATION} + \varepsilon \\
\text{where} \quad & P = E(\mathrm{COOP} = 1|\mathbf{X}) \\
\text{and} \quad & \mathbf{X} = \{\mathrm{PRICEDIS}, \mathrm{PRICEPROD}, \mathrm{RESERVE}, \mathrm{DEPTH}, \\
&\quad \mathrm{CAPACITY}, \mathrm{WELLSDISC}, \mathrm{DURATION}\}.
\end{aligned}$$

To control for the potential endogeneity of the explanatory variable, CAPACITY, a 2-stage logit model is also estimated. In the first stage linear regression, the exogenous variable DEPTH is used as an instrumental variable to estimate a proxy variable $\widehat{\mathrm{CAPTY}}$, resembling the original CAPACITY.

In the second stage logit model, $\widehat{\text{CAPTY}}$ is included as a regressor to replace CAPACITY. The 2-stage logit model is expressed as:

$$
\begin{aligned}
\text{Stage 1:}\quad & \text{CAPACITY} = \alpha_1 + \delta\text{DEPTH} + \varepsilon_1 \\
\text{Stage 2:}\quad & \ln\left(\frac{P}{1-P}\right) = \alpha_2 + \beta^{\text{pd}}\text{PRICEDIS} + \beta^{\text{pp}}\text{PRICEPROD} \\
& \qquad + \beta^{\text{rs}}\text{RESERVE} + \beta^{\text{c}}\widehat{\text{CAPTY}} \\
& \qquad + \beta^{\text{w}}\text{WELLSDISC} + \beta^{\text{dn}}\text{DURATION} + \varepsilon_2 \\
\text{where}\quad & P = E(\text{COOP} = 1|\mathbf{X}) \\
\text{and}\quad & \mathbf{X} = \{\text{PRICEDIS}, \text{PRICEPROD}, \text{RESERVE}, \widehat{\text{CAPTY}}, \\
& \qquad \text{WELLSDISC}, \text{DURATION}\}.
\end{aligned}
$$

Table 2 reports the results from the logit regression of cooperation. In both simple logit and 2-stage logit model, the negative coefficients of PRICEPROD are consistent with Hypothesis 1. The real option exercise price has a negative effect on the probability of cooperation. For one cent increase in the initial gas price, the probability that firms build a cooperative gas plant decreases by a factor of 0.53 in the 2-stage logit model, or 0.58 in the simple logit model.[4] This is because as gas prices increase, the follower's real option exercise hurdle price is easier to reach. Therefore the follower's willingness to play cooperatively decreases, since it has a more viable chance of building

[4]Here, 0.5329 is calculated as $\exp^{-0.6294}$ and 0.5829 is calculated as $\exp^{-0.5397}$. As with many other papers interpreting logit results, instead of interpreting the log odds of the dependent variable, we exponentiate the coefficients and interpret them as odds-ratios.

Variables	Simple logit			Variables	2-stage logit		
					Stage 1		
				capacity	Coef.	Std. Err	t
				depth	0.8627	0.1348	6.40
				constant	-107.9803	226.9679	-0.48
					Stage 2		
Coop	Coef.	Std. Err.	z	Coop	Coef.	Std. Err.	z
pricedis	0.5556	0.4259	1.30	pricedis	0.4590	0.4037	1.14
priceprod	-0.5397	0.1328	-4.06	priceprod	-0.6294	0.1412	-4.46
reserve	-1.51E-05	0.0000	-1.25	reserve	-1.08E-05	0.0000	-1.02
wellsdisc	-0.0020	0.0022	-0.91	wellsdisc	0.0006	0.0003	2.51
duration	0.0070	0.0144	0.48	duration	-0.0024	0.0020	-1.22
depth	0.0004	0.0002	1.65	depth	-	-	-
capacity	0.0004	0.0002	2.75	captyhat	0.0004	0.0139	0.03
constant	0.65637	0.4608	1.42	constant	1.114297	0.415305	2.68
N	323			N	327		
Chi-square	69.80			Chi-square	58.05		
Adj. R^2	0.1669			Adj. R^2	0.1361		

Table 2: **Logit models of cooperation.** It provides the logit model estimates for cooperation. The dependent variable is COOP, indicates whether the gas processing plant is cooperative. PRICEDIS is the natural gas price at the discovery time. PRICEPROD is the natural gas price at the time of production. RESERVE is the initial reserve quantity of the field. DEPTH is the average depth of all production wells within particular field, representing the drilling costs. CAPACITY is the plant's daily processing capacity, proxying the construction cost of the plant. WELLSDISC is the total number discovery wells within certain field, representing the level of network effect. DURATION measures the waiting period (investment lag) between discovery year and start production year.

its own plant. If the leader does not lower the lease rate accordingly, the bargaining game may end in a non-cooperative equilibrium, which reduces the probability of cooperation.

The coefficient of WELLSDISC is positive (0.06), which confirms Hypothesis 3. The competition effect is dominated by the network effect and the number of discovery wells has a positive effect on cooperation. For every unit increase in WELLSDISC, the probability of building a cooperative plant increases by a factor of 1.0006. In a more crowded field, whichever firm builds the plant first will become the leader and have the ability of extract rents from the followers. All firms possessing a similar reserve size will share a similar exercise price and want to seize this opportunity. The competition level rises. Meanwhile, firms are also aware of the beneficial network effect that becomes stronger because more firms may start producing together. As the network effect dominates the competition effect, firms are more willing to cooperate rather compete with each other when more there are more discovery wells.

Hypothesis 2 is not strongly confirmed, since the coefficient of reserves is not statistically significant in either of these two models. However, the negative sign of reserve coefficient does indicate the right direction predicted by Hypothesis 2. The extremely small coefficients, -0.0000151 in simple logit and -0.0000108 in 2-stage logit are caused by the large magnitude of reserves. Capacity is found to have positive effect on the probability of cooperation in the simple logit model only. Once the heterogeneity problem is purged in the 2-stage logit model using DEPTH as the instrumental variable, the effect of capacity ceases to be statistically significant. This shows that larger plant capacity may not be the cause but the outcome of firms' cooperative investment, i.e., cooperative plants are normally larger in order to accommodate natural gas from multiple fields.

3.2 The duration model of investment timing for building a gas processing plant

To analyze the effect of gas price, price volatility, quantity of gas reserves and the network effect (competition effect) on the investment time lag, I use the framework of duration analysis. Denote the dependent variable t as the observed investment time lag between the reserve discovery time t_1 and the production startup time t_2. The lag t is measured as $t = t_2 - t_1$, and has a probability density of $f(t)$, and associated cumulative distribution function of $F(t)$. The survival function is $S(t) = 1 - F(t)$. The hazard function is $h(t) = \frac{f(t)}{S(t)} = \frac{f(t)}{1-F(t)}$. The functional form of $h(t)$ depends on the distribution of t. Based on this hazard function, $h(t)$, a proportional hazard (PH) model conditional on time-invariant covariates $\mathbf{x}$ can be defined as

$$h(t, \alpha; \mathbf{x}, \lambda) = h_0(t, \alpha)\theta(\mathbf{x}) \tag{1}$$

where $h_0(t, \alpha)$ is the baseline hazard function with parameter α and is common to all units in the population. The individual hazard functions, $h(t, \alpha; \mathbf{x}, \lambda)$

differ proportionately from the baseline hazard by a nonnegative factor $\theta(\mathbf{x})$. The function $h_0(t,\alpha)$ may either be left unspecified which gives the Cox proportional hazard, or be assumed to follow a specific distribution such as the exponential, Weibull[5] or Gompertz distribution as described in Lee and Wang (2003).

Using the Wooldridge (2002) formulation, $\theta(\mathbf{x})$ is normally parameterized as $\theta(\mathbf{x}) = \exp(\lambda\mathbf{x})$, where λ is a vector of parameters and $\mathbf{x}$ is the vector of explanatory variables. To interpret the estimates of λ, the hazard function needs be represented in the regression form

$$\ln h(t,\mathbf{x}) = \lambda\mathbf{x} + \ln h_0(t).$$

The explanatory variable vector $\mathbf{x}$ is defined as:

$$\begin{aligned}\{&\mathrm{COOP}, \mathrm{PRICEDIS}, \mathrm{PRICEPROD}, \mathrm{RESERVE}, \mathrm{DEPTH},\\ &\qquad\qquad\qquad\qquad \mathrm{CAPACITY}, \mathrm{WELLSDISC}\}\end{aligned}$$

which includes the discovery price, production price, initial reserve quantity, average well depth, plant capacity and the number of discovery wells within

[5] The Weibull distribution is a generalization of the exponential distribution of a Poisson Process, which has a constant hazard rate over time. A full specification of the Weibull distribution hazard function includes: $f(t) = \alpha\theta t^{\alpha-1}\exp(-\theta t^{\alpha}); S(t) = \exp(-\theta t^{\alpha}); F(t) = 1-\exp(-\theta t^{\alpha}); h(t) = -\frac{d\ln S(t)}{dt} = \alpha\theta t^{\alpha-1}$ where, $\theta = \exp(\mathbf{x}\lambda)$ and α is a parameter. If $\alpha > 1$, the hazard is monotonically increasing (positive duration dependence); if $0 < \alpha < 1$, the hazard is monotonically decreasing (negative duration dependence). The baseline hazard for the Weibull distribution is $h_0(t,\alpha) = \alpha t^{\alpha-1}$, where α is a nonnegative parameter.

individual field.

An alternative assumption here would be the accelerated failure time (AFT) model which requires the choice of hazard function distribution. The AFT model is expressed as a linear function of the explanatory covariates,

$$\ln t = \lambda \mathbf{x} + \nu$$

where $\mathbf{x}$ is the covariate vector same as in PH model, λ is the regression coefficient vector, and ν is the residual term. The distribution of the residual determines the regression model. If ν is assumed normal, the lognormal AFT model is obtained[6]. If ν is assumed to follow logistic distribution, the log-logistic AFT model is obtained. Similarly, assuming ν follows extreme-value theory yields the exponential AFT model or the Weibull AFT model. Assuming an incomplete gamma function for ν gives the generalized gamma AFT model.

At this stage, it is premature to determine whether the investment lag can be characterized by positive or negative duration dependence. Simply assuming an arbitrary distribution that displays certain characteristic may lead to estimation bias. Therefore, both proportional model and accelerated failure time model are estimated using all available distributions, which closely resembles Favero et al. (1994), Kiefer (1988) and Hurn and Wright (1994). Under PH model, four models are estimated including the semi-parametric

[6] Log-normal distribution leads to a non-monotonic hazard function, whose hazard rate initially increases and then decreases with time.

Cox PH model, exponential PH model, Weibull PH model and Gompertz PH model. Under AFT model, five models are estimated including exponential AFT model, Weibull AFT model, lognormal AFT model, log-logistic AFT model and generalized gamma AFT model.

The following two hypotheses will be tested with the duration model.

Hypothesis 4 The duration of the investment lag is expected to depend negatively on the gas price and initial reserves. Gas price and initial reserve positively related to firm's profit. When the gas price rises or firms have increased estimation reserve estimates, the expected profit would rise and firms are more likely to exercise the real option to invest.

Hypothesis 5 The competition effect and the network effect may decrease or increase the investment lag depending on which effect dominates. Grenadier (2002), Leahy (1993) and Kogan (2001) argue that competition erodes real option values and reduces the development delay to zero-NPV rule, which means competition should have negative effect on the investment lag. Conversely, Novy-Marx (2007) argues that in industries with significant opportunity cost or supply side heterogeneity, this erosion effect of competition is not strong enough to offset the real option value, and firms may delay even further than the optimal investment threshold derived from the standard real option model. In the case of developing natural gas fields, the opportunity costs exist because, once the field is developed, it cannot be developed second time.[7]

[7] This differs from the opportunity costs defined in Novy-Marx model, which assumes

The firms are also heterogeneous because the sizes of their reserves are quite different. Another important factor is the network effect which tends to increase the investment lag. It is thus interesting to test which one is the dominating factor in the gas production industry. The estimation of the duration analysis shall be able to verify either one of these two results.

the firm can reinvest again, because the resource is renewable

Panel A. Proportional hazard

	Cox Proportional Hazard			Exponential Hazard			Weibull Hazard			Gompertz Hazard		
Duration	Haz. Ratio	Coefficient	z	Haz. Ratio	Coefficient	z	Haz. Ratio	Coefficient	z	Haz. Ratio	Coefficient	z
coop	0.9290	-0.0736	-0.58	1.0012	0.0012	0.01	1.0022	0.0022	0.02	0.9266	-0.0763	-0.61
pricedis	4.8226	1.5733	8.13	2.0697	0.7274	4.10	4.0523	1.3993	7.34	5.1257	1.6343	8.43
priceprod	0.5812	-0.5426	-7.56	0.7909	-0.2346	-4.36	0.6246	-0.4707	-6.92	0.5729	-0.5570	-7.69
reserve	1.0000	-2.82E-06	-0.61	1.0000	-1.49E-06	-0.32	1.0000	-1.67E-06	-0.36	1.0000	-2.32E-06	-0.50
wellsdisc	0.9983	-0.0017	-1.88	0.9988	-0.0012	-1.31	0.9979	-0.0021	-2.29	0.9982	-0.0018	-1.93
depth	1.0002	0.0002	2.16	1.0001	0.0001	0.93	1.0002	0.0002	1.70	1.0002	0.0002	2.09
capacity	1.0001	1.16E-04	3.65	1.0001	8.11E-05	2.63	1.0001	1.39E-04	4.34	1.0001	0.0001	3.92
Constant		-		0.0564	-2.8751	-15.10	0.0014	-6.5471	-17.13	0.0143	-4.2497	-18.27
p		-			-		-	2.1856	0.10		-	
sigma		-			-			-			-	
gamma		-			-			-		-	0.0927	15.96
N	298			298			298			298		
Log-likelihood	-1336.57			-344.59			-245.70			-218.26		
AIC*	2687.14			705.18			509.39			454.52		

Panel B. Accelerated failure-time hazard

	Exponential AFT		Weibull AFT		Lognormal AFT		Log-logistic AFT		Generalized gamma AFT	
Duration	Coefficient	z	Coefficient	z	Coefficient	z	Coefficient	z	Coefficient	z
coop	-0.0012	-0.01	-0.0010	-0.02	0.0028	0.04	0.0142	0.20	0.0085	0.18
pricedis	-0.7274	-4.10	-0.6402	-7.67	-0.8663	-7.91	-0.8549	-7.02	-0.6064	-8.04
priceprod	0.2346	4.36	0.2153	7.24	0.2660	9.65	0.2265	8.47	0.2126	6.24
reserve	1.49E-06	0.32	7.65E-07	0.36	2.11E-06	0.68	2.37E-06	0.87	1.34E-07	0.08
wellsdisc	0.0012	1.31	0.0009	2.29	0.0015	2.68	0.0011	2.15	0.0006	1.61
depth	-0.0001	-0.93	-0.0001	-1.70	-0.0001	-1.58	-0.0001	-2.28	-0.0001	-1.15
capacity	-8.11E-05	-2.63	-6.37E-05	-4.35	-1.01E-04	-5.22	-9.52E-05	-4.75	-4.12E-05	-2.64
Constant	2.8751	15.10	2.9955	32.13	2.6893	23.95	2.8944	27.30	3.0844	33.73
p	-		2.1856	1.99	-		-		-	
sigma	-		-		0.6137	0.57	-		0.3747	0.32
gamma	-		-		-		0.3343	0.30	-	
kappa	-		-		-		-		1.6589	6.74
N	298		298		298		298		298	
Log-likelihood	-344.59		-245.70		-277.36		-272.68		-240.62	
AIC*	705.18		509.39		572.73		563.36		501.25	

* AIC refers to Akaike information criterion.

Table 3: **Duration models of investment lag.** It presents the duration model analysis for investment lag assuming four different Hazard distribution function. The dependent variable is DURATION which measures the waiting period (investment lag) between discovery year and start production year. COOP indicates whether the gas processing plant is cooperative. PRICEDIS is the natural gas price at the discovery time. PRICEPROD is the natural gas price at the time of production. RESERVE is the initial reserve quantity of the field. DEPTH is the average depth of all production wells within particular field, representing the drilling costs. CAPACITY is the plant's daily processing capacity, proxying the construction cost of the plant. WELLSDISC is the total number discovery wells within certain field, representing the level of network effect.

Table 3 presents the results from aforementioned four PH models in panel A and five AFT models in panel B. To determine which model is a better fit, the log-likelihood and Akaike information criterion (AIC) need to be calculated.[8] Among four proportional hazard models, the Gompertz model is the best as it has the largest log-likelihood of -218.26 and smallest AIC of 454.52. Among five accelerated failure time models, the generalized gamma model is the best as it has the largest log-likelihood of -240.62 and smallest AIC of 501.25. Overall, Gompertz PH model is a better fit than generalized gamma AFT model since it has larger log-likelihood and smaller AIC. Therefore, the focus of the analysis will be put on Gompertz model. In Gompertz model, gamma equals to 0.0927, greater than 0, which means the hazard rate of failure rises with time. As firms wait longer, they are more likely to stop waiting and start the investment.

The discovery price and production price have opposite effects on the investment lag. PRICEDIS has a hazard ratio of 5.13 in Gompertz model, which suggests that if the discovery price increases by one cent, the firms are roughly five times more likely to start the investment. This is consistent with hypothesis 4 and standard real option theory: as commodity price rises, firms

[8]When parametric hazard models are not nested in the data, model comparison using likelihood ratio or Wald test may not be appropriate. As such, Akaike (1974) proposed penalizing the log-likelihood to reflect the number of parameters being estimated in a particular model and comparing them. In generalized gamma model, I also test the hypothesis that $\kappa = 0$ (test the appropriateness of the lognormal), and the hypothesis that $\kappa = 1$ (test for the appropriateness of the Weibull). The z value for $\kappa = 0$ is 6.74, suggesting suggesting that the lognormal model is not an appropriate model for analyzing investment lag. The p value for $\kappa = 1$ is 0.74%, which provides some support for the Weibull model.

are more likely to exercise the real option to invest. The negative coefficient of PRICEDIS in generalized gamma model also verifies that the price at discovery has negative effect on investment lag.[9] One cent increase in the price at discovery would reduce the investment lag by 0.61 year. PRICEPROD has a hazard ratio of 0.57 indicating that firms are about 40% less likely to start the investment if the optimal real option exercise price increases by one cent. Generalized gamma model gives PRICEPROD a positive coefficient of 0.21 suggesting the price at production has a positive effect on investment lag. One cent increase in the price at production would increase the investment lag by 0.21 year. The intuition is that the price at the time of production represents the threshold or hurdle price for development, which increases with development costs. Normally, higher development cost entails longer waiting period.

Hypothesis 4 regarding the initial reserve is not strongly confirmed. The hazard ratio for reserves is one and insignificant. However, the covariate RESERVE has a negative coefficient, -2.32×10^6 which indicates the correct direction — negative effect of initial reserves on firms' investment lag. The extreme small coefficient is again caused by the large magnitude of reserves. WELLSDISC has a hazard ratio of 99.82% indicating that if the competition or network effect increases by one unit, firms are 0.18% less likely to start the

[9] In Gompertz PH model and generalized gamma AFT model, the sign of coefficients are opposite because AFT model is expressed in terms of $\ln t$, the survival time (investment lag), whereas PH model is expressed as the hazard rate, the probability of the failure (investment)

investment. Although this negative effect of the network effect on investment lag is quite small, it supports Novy-Marx (2007) argument that in industries with opportunity cost and heterogeneity, competition is not enough to fully erode the real option value. Other factors such as the network effect may cause the investment lag to be even longer. The hazard ratios of average well depth, DEPTH and plant capacity, CAPACITY are slightly greater than one and statistically significant. Their effects on the firms' probability of investing are marginally positive.

4 Conclusion

The competitive real option literature has developed various equilibrium models (Bertrand, Cournot, or Stackelberg) for firms' investment decisions under competition. This research provides another equilibrium possibility — cooperative equilibrium in which firms share common production facility and both benefit from the network effect. Strong evidence is provided to show that firms investment decisions are strategic at least in the natural gas industry. Sometimes they compete with each other by investing earlier to preempt others. Sometimes, they may cooperate with each other in order to take the advantage of network effect. The choice between competition and cooperation may depend on two factors, real option exercise price (the price at which the production starts) and the level of competition or the network effect. Higher option exercise price will decrease the possibility of cooperation, whereas higher network effect will increase the possibility of cooperation.

This research also provides the empirical evidence in favor of Novy-Marx (2007) argument. That is, in industries with significant opportunity costs such as oil and gas industry, supplier heterogeneity or network effect may offset the erosion effect of competition on real option value to delay the investment. Firms in these industries will not start investment once the NPV rises to zero. Instead, their investments are typically delayed. The duration the investment delay is affected by commodity price and the level of network effect. Commodity prices have a negative effect on the duration of investment lag. The network effect has an positive effect on the duration of investment lag.

References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transaction and Automatic Control*, AC-19:716–723.

Boyer, M., Lasserre, P., Mariotti, T., and Moreaux, M. (2001). Real options, preemption, and the dynamics of industry investments.

Brennan, M. J. and Schwartz, E. (1985). Evaluating natural resource investments. *Journal of Business*, 58(2):135–157.

Bulan, L. T. (2005). Real options, irreversible investment and firm uncertainty: New evidence from u.s. firms. *Review of Financial Economics*, 14(3/4):255–279.

Bulan, L. T., Mayer, C. J., and Somerville, C. T. (2002). Irreversible investment, real options, and competition: Evidence from real estate development.

Capozza, D. R. and Sick, G. A. (1991). Valuing long-term leases: The option to redevelop. *The Journal of Real Estate Finance and Economics*, 4(2):209–223.

Dixit, A. (1995). Irreversible investment with uncertainty and scale economies. *Journal of Economic Dynamics and Control*, 19(1–2):327–350.

Dixit, A. K. and Pindyck, R. S. (1994). *Investment under Uncertainty*. Princeton University Press, Princeton, N.J.

Favero, C. A., Pesaran, M. H., and Sharma, S. (1994). A duration model of irreversible oil investment: Theory and empirical evidence. *Journal of Applied Econometrics*, 9:S95–S112.

Fudenberg, D. and Tirole, J. (1985). Preemption and rent equalization in the adoption of new technology. *Review of Economic Studies*, 52(170).

Garlappi, L. (2001). Preemption risk and the valuation of R&D ventures.

Grenadier, S. R. (1996). The strategic exercise of options: Development cascades and overbuilding in real estate markets. *Journal of Finance*, 51(5):1653 – 1679.

Grenadier, S. R. (2002). Option exercise games: An application to the equilibrium investment strategies of firms. *Review of Financial Studies*, 15(3):691–721.

Huisman, K. J. M. and Kort, P. M. (2004). Strategic technology adoption taking into account future technological improvements: A real options approach. *European Journal of Operational Research*, 159(3):705–728.

Hurn, A. S. and Wright, R. E. (1994). Geology or economics? testing models of irreversible investment using north sea oil data. *The Economic Journal*, 104(423):363–371.

Kiefer, N. M. (1988). Economic duration data and hazard functions. *Journal of Economic Literature*, 26(2):646–679.

Kogan, L. (2001). An equilibrium model of irreversible investment. *Journal of Financial Economics*, 62:201–245.

Lambrecht, B. and Perraudin, W. (2003). Real options and preemption under incomplete information. *Journal of Economic Dynamics and Control*, 27(4):619–643.

Leahy, J. V. (1993). Investment in competitive equilibrium: the optimality of myopic behavior. *Quarterly Journal of Economics*, 108(4):1105–1133.

Lee, E. T. and Wang, J. W. (2003). *Statistical Methods for Survival Data Analysis*. New York: Wiley, 3rd edition.

Mason, R. and Weeds, H. (2005). Can greater uncertainty hasten investment? Formerly: "Irreversible Investment with Strategic Interactions" and "Networks, Options and Pre-emption".

Murto, P. and Keppo, J. (2002). A game model of irreversible investment under uncertainty. *International Game Theory Review*, 40(2):127–140.

Novy-Marx, R. (2007). An equilibrium model of investment under uncertainty. *The review of Financial Studies*, 20(5):1461–1502.

Sick, G. A. (1995). Real options. In Jarrow, R., Maksimovic, V., and Ziemba, W. T., editors, *Finance*, volume 9 of *Handbooks in Operations Research and Management Science*, chapter 21, pages 631–691. North Holland.

Sick, G. A. and Li, Y. (2007). Real options, sequential bargaining game and network effects in natural gas production. SSRN Working Paper Series.

Smit, H. T. J. and Trigeorgis, L. (2004). *Strategic Investment: Real Options and Games*. Princeton University Press.

Thijssen, J. J. J., Huisman, K. J. M., and Kort, P. M. (2006). The effects of information on strategic investment and welfare. *Economic Theory*, 28(2):399–424.

Trigeorgis, L. (1996). *Real Options: Managerial Flexibility and Strategy in Resource Allocation*. MIT Press, Cambridge, MA.

Wooldridge, J. M. (2002). *Econometric Analysis of Cross Section and Panel Data*. The MIT Press.