Upstream-Downstream Investment In a Partial Integrated Industry

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Abstract

The thesis proposes a model of the partially integrated oil industry, with a strict division of the production process into upstream and downstream. The model takes the form of a static non-cooperative game with the three types of players: pure upstream, pure downstream and integrated firms. The focus of the analysis is on the differences in incentives and optimal behavior between the types of the firms, with special emphasis on investment decisions and production cost asymmetry. Standard game theory tools and simulations are used in order to assess the investment behavior of firms and their interaction. The provided analysis also evaluates the strategic advantages and consideration of integrated firms. The thesis contributes to the understanding of the investment incentives of firms, provides insights into the effects and origins of production cost asymmetry in a vertically integrated industry and tries to explain the increasing share of specialized firms in the industry.

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Introduction

Vertical integration is a well-defined concept; it is a form of business organization in which one company controls all stages of production of a good, from the acquisition of raw materials to the retailing of the final product. However, the purposes to integrate vertically have considerably changed over time. In the 19th century, vertical integration was mainly concerned with achieving economies of scale, while in the 20th century, the decision to integrate vertically was typically related to the security of supply, for backward integration, and security of market, for forward integration. That is, it was cheaper for a firm to perform the role of the supplier and distributor than to negotiate with other parties. The studies undertaken by Mitchell (1976) and Rusin and Siemon (1979) have provided empirical support to this idea by discovering a positive effect of supply uncertainty on the decision to integrate. Nevertheless, in the late 20th century, many large corporations started shutting down or selling some of their supplement units, reducing the levels of vertical integration.

The popular idea is that in the recent past vertical disintegration was driven by the rapid development of telecommunication technologies, which provided much lower transaction costs between the participants of the market. As lower transaction costs can be achieved using modern telecommunication technologies rather than by vertically integrating, firms start to disintegrate vertically. This phenomenon is widely known as the "Law of Diminishing Firms" or "Coase's Law" (named after Ronald Coase, 1991 Nobel Prize Laureate). The law states that a decrease in transaction costs implies a decrease in the size of the firm. The popularity of this idea can be explained by its intuitive appeal and clear testable propositions arising from the theory (Barrera-Rey, 1995). As it is concluded by Whinston (2003), "the transaction cost approach to the organization of firms has been one of the most significant advances in the industrial organization over last 25 years" and the theory built on it has high predictive power. However, it is not the only factor that can drive vertical integration or disintegration.

Another hypothesis that attracted a lot of attention was proposed by Stigler (1951). It states that the typical development of the growing industry should be vertical disintegration, whereas a declining industry should promote vertical integration. His argument was that in the case of increasing demand it is more profitable for a firm to outsource its inputs from a large scale specialized firm than to produce itself on the small scale. The validity of this hypothesis has been widely tested in the literature, but the outcome varies across different studies and is sensitive to assumptions (Elberfeld, 2002). Thus, as it was pointed out by Dufeu (2004), these results are inconclusive.

In addition, there is a large theoretical and empirical literature that explores the causes and effects of vertical integration. Most of the models of vertical integration describe the behavior of integrated and non-integrated firms identically (Gaudet et al, 1999). The reason for this simplification is that in many industries there is no explanation why different firms can have different upstream/downstream costs in the long run. However, in the natural resource industries (such as oil industry), there is a clear cost asymmetry in the upstream production exogenously determined by the differences in resource fields controlled be companies. Moreover, some downstream firms have proved to be more successful then others. Thus, it makes sense to consider some cost asymmetries among firms.

A lot of studies present models of successive oligopoly, highlighting the influence of vertical integration on the price/quantity decisions of the firms. However, only a small number of attempts have been made to describe the effect of firms' structure on investment decisions. In one of these papers, Schmutzler and Bühler (2005) examined how vertical integration can affect the cost-reducing investments undertaken by firms. They found that integrated firms tend to invest downstream more than their specialized rivals do.

A considerable fraction of the literature concentrates on oil, the absolute majority of which are empirical studies; however, the theoretical approach deserves more interest, as it can provide more insights about the incentives of firms' behavior. The historical model of the oil industry is vertical integration along the supply chain from crude exploration and production (upstream) through refining and marketing (downstream) to retail. The degree of vertical integration is relatively high and persistent, which still seems to be the way of thinking for many in this industry. There are, however, tendencies that question this conventional wisdom: the best performing oil companies recently seem to be the pure play upstream or downstream companies. Moreover, larger and larger portions of oil exploration and production are carried out by national oil companies, which are less integrated (more upstream oriented), than the major internationals. This means that more studies should be done to analyze these new tendencies in the oil industry.

Therefore, the aim of this thesis is to build a model of the oil industry, which describes the investment decisions of integrated and specialized companies, taking into account the main characteristics of the industry. The presented analysis is inspired by and closely related to the paper written by Gaudet et al (1999), which examines the two-stage game model of a partially integrated industry and highlights the effects of upstream cost asymmetry on an integrated firm's interaction with the non-integrated sector of the industry and on its relative upstream-downstream specialization. In this paper, Gaudet et al describe a clear strategic advantage of the integrated firms through the interaction on the crude oil market, but do not account for investing possibilities. Nevertheless, there is different aim and a considerable difference in the specification of the model provided below, which allows us to analyze the investment decisions of firms. The thesis contributes to understanding of investment incentives of firms and provides insights about production cost asymmetry in the vertical integrated industry.

The remainder of the thesis is organized as follows. Chapter 1 provides an overview of the oil industry. In Chapter 2, the basic two-stage model is presented and analyzed, while Chapter 3 presents the extensions allowing for investment and illustrative simulations.

Chapter 1
Oil Industry Overview

The demand for oil driven by the fast growing oil consumption in the non-OECD Asian countries has dramatically increased in the recent past and is expected to grow in the near future. However, the production of crude oil is highly constrained by the limited reserves, which results in the fast growing price of oil. Nevertheless, the industry plays a most important role in the world economy and is the largest industry in terms of dollar value; its outputs account for more than 40% of the world's energy consumption and are used as raw materials for many chemical products. That is why the oil industry is a subject of extensive business and academic research.

As already noted in the introduction, the oil industry consists of the global processes of exploration, extraction, refining, transporting, and marketing of oil products. These processes are usually divided into two major components: upstream and downstream ones. However, sometimes midstream operations are considered separately, which are the final operations of upstream.

The corporate structure of the industry has evolved spectacularly over time. In the 1960s, multinational companies like Shell, BP, and Mobil formed the overwhelming part of the industry. However, Glomsrod and Lindhol (2004) state that the environment of oil giants has changed considerably since the days of the Seven Sisters[1]. Nowadays, the sisters are reduced to four and have access only to 10% of the world's oil reserves, while state-run companies exercise control over more than 70% percent of crude oil production, and pure downstream producers have

[1] The seven major multinational oil companies in the 1960s: Exxon, Mobil, Gulf, Socal, Texaco, Shell, BP and The Lobby

significantly increased their market share. Thus, specialized firms have become at least as important as their integrated rivals, which should be taken into account in any analysis of the industry. Table 1 in Appendix 1 shows the substantial difference in the corporate structure of the oil extraction industry between 1972 and 2000.

One fact that has remained constant over time is that, just like in most natural industries, there is a substantial upstream cost asymmetry among producers. Even though direct data on upstream costs is not publicly available and it may not even exist, because of its great value and measurement difficulties, there are strong reasons to believe that these costs can be very diverse. It is apparent that the technology, skills and equipment needed for crude oil extraction differ greatly among the locations of the oilfields, e.g. it is much easier and cheaper to extract oil in OPEC region, where it lies almost under the surface, than to take it out from a sea shelf. Moreover, in most cases a negative relation between the cost of extraction and the size of reserves is broadly recognized. Consequently, the size of the reserves can be used as an indicator of at least an important part of cost asymmetry among upstream firms. Table 2 in Appendix 2 shows the distribution of oil reserves of top 46 integrated firms and indicates substantial differences in reserves, supporting upstream cost asymmetry.

Though there is no clear evidence on downstream cost asymmetry, the reasoning can be taken from organizational economics, as there are always costs associated with the organization of production within the firm. Barrera-Rey (1995) points out two clear reasons of diseconomies of vertical integration: managerial diseconomies, which arise because managerial ability is a scare resource, and an integrated firm requires more knowledge and skills, and, consequently more managerial decisions must be delegated; and diseconomies of control, as the complexity and the degree of differentiation of the firm structure increases. Moreover, the variety of stage-specific production processes makes the acquisition of new knowledge and technology more complicated, and therefore, more expensive. From Table 2 in Appendix 2 we can see that even firms with nearly equal upstream productions can greatly differ in their refining levels, which also supports downstream cost asymmetry. One more reason to believe in the upstream cost asymmetry at least between integrated and non-integrated firms is that we can persistently observe upstream-specialized firms on the market. Otherwise, the presence of the strategic advantage and extinction of double marginalization in integrated firms would force purely upstream firms to integrate or to exit the market.

Chapter 2

Basic Two-Stage Model

The aim of this chapter is to design and analyze a model of the partially integrated oil industry, taking into account the features of the industry discussed above. The model takes the form of a two-stage static non-cooperative game, with the players aiming to maximize their profits. In the real world, both crude oil and final product markets are oligopoly markets, where at least some of the firms can considerably influence the prices, so the quantity competition framework (ala Cournot) is used for both of these markets. For the reasons discussed in the previous chapter and similary to Dufeu (2004) and Gaudet et al (1999), we assume that the firms differ in their costs of downstream and upstream production.

In this chapter and the next one, the computational software, Mathematica 5.0 was used for computations and simulations.

2.1 General Setup

The model consists of two vertically related industries and three types of producers: integrated, pure upstream and pure downstream. It is assumed that intermediate and final products are both homogeneous. An upstream firm extracts crude oil, which is used by a downstream firm to produce the final good with a one-to-one technology[2]. An integrated firm is involved in both processes. The costs of production incurred by integrated, upstream and downstream firms are denoted by $C^i(x^i, y^i)$, $C^u(x^u)$ and $C^d(y^d)$, where x stands for the amount of the crude oil, y

[2] One unit of the crude oil is required to produce one unit of the final product.

stands for the amount of the final good produced and superscripts i, u and d denote integrated, upstream and downstream, respectively. Following Dufeu (2004), we assume that the firms can differ in their costs of downstream and upstream productions.

The price of the crude oil w is affected by both industries and is set to equalize demand and supply. The price of the refined product depends on the total amount produced and is given by the inverse demand function:

$$p = p(\sum y^d + \sum y^i) = p(Y) \tag{2.1}$$

The game proceeds as follows. In the first stage, upstream and integrated firms simultaneously choose the amount of the intermediate good to be delivered to the market, i.e. upstream firms just decide how much to produce and integrated firms set their interaction with the intermediate market, which is denoted by $s^i = x^i - y^i$. Negative s means that an integrated firm extracts less crude oil than it refines and buys the rest from the market; positive s means that a firm sells a part of its crude.

In the second stage, downstream and integrated firms simultaneously decide how much of the final good to deliver to the consumers. At the same time, they set the amount of crude they buy/sell from the intermediate market, and the price of crude oil w is determined by the market forces.

At this point, we are able to write down the general form of the profit functions of the firms to be maximized in equilibrium:

$$\pi^u = x^u w - C^u(x^u) \tag{2.2}$$

$$\pi^d = y^d p(Y) - y^d w - C^d(y^d) \tag{2.3}$$

$$\pi^i = y^i p(Y) + (x^i - y^i)w - C^i(x^i, y^i) = y^i p(Y) + s^i w - C^i(y^i + s^i, y^i) \tag{2.4}$$

The described game can not be solved in the general setup, and therefore, the next section provides the solution of the specific form of the model.

2.2 The Solution of the Model

Following the general setup, in this section we assume that the firms are strategic players on the crude oil market and can affect the price of the crude. In order to be able to solve the game, we need to impose some simplifying assumptions and define the function specifications. First of all, we constrain the analysis to three firms, representing the three types described above (pure upstream, pure downstream and integrated). This simplification will not distort any qualitative implications of the model while making calculations and examination much easier.

As in most of the related literature, we assume a linear demand function for the final good, so (2.1) modifies into:

$$p = p(Y) = a - bY \tag{2.5}$$

Here we also assume that the demand for the final good is high enough to rule out the corner solution and to keep all the players in the market (parameter a is high enough).

We assume that crude oil can be extracted with the constant marginal cost denoted c_u, and its refining takes place with the constant marginal cost denoted c_d. Fixed costs are put to be zero. As mentioned before, there is a cost asymmetry between integrated and specialized firms, so $c_u^i \neq c_u^u$ and $c_d^i \neq c_d^u$.

Taking into account the assumptions described above, the profit functions of the firms can be written as:

$$\pi^u = x^u (w - c_u^u) \tag{2.6}$$

$$\pi^d = y^d(a - b(y^d + y^i)) - y^d w - y^d c_d^d \tag{2.7}$$

$$\pi^i = y^i(a - b(y^d + y^i)) + s^i w - y^i c_d^i - (y^i + s^i)c_u^i \tag{2.8}$$

Following the standard technique of solving multi-stage games, we start from the last (downstream) stage, where the firms simultaneously choose the quantity to refine in order to maximize their profits described by (2.7) and (2.8):

$$\max_{y^i}\left\{y^i(a - b(y^d + y^i)) + s^i w - y^i c_d^i - (y^i + s^i)c_u^i\right\} \tag{2.9}$$

$$\max_{y^d}\left\{y^d(a - b(y^d + y^i)) - y^d w - y^d c_d^d\right\} \tag{2.10}$$

The first order conditions yield the following reaction functions:

$$y^i = \frac{a - c_d^i - c_u^i - by^d}{2b} \tag{2.11}$$

$$y^d = \frac{a - c_d^d - w - by^i}{2b} \tag{2.12}$$

Solving this system, we can find the equilibrium of the downstream stage:

$$y^i = \frac{a - 2c_d^i - 2c_u^i + c_d^d + w}{3b} \geq 0 \tag{2.13}$$

$$y^d = \frac{a - 2c_d^d - 2w + c_d^i + c_d^u}{3b} \geq 0 \tag{2.14}$$

Before proceeding to the next stage of the game, we need to characterize the demand for the intermediate good. As demand should equal supply, the key equation is

$$y^d = x^u + s^i \tag{2.15}$$

Plugging y^d from (2.14) into (2.15) and solving for the price of the crude oil w, we get the inverse demand function:

$$w = \frac{1}{2}(a + c_d^i + c_u^i - 2c_d^d - 3b(s^i + x^u)) \tag{2.16}$$

The interesting implication from (2.16) is that there is a positive effect of the downstream costs of integrated firm on the price of the crude. The reason for that is that an increase of these costs lowers the competitiveness of the integrated firm on the final product market, which makes the downstream firm produce more and, hence, increases the demand on the crude oil market. However, there is also a negative effect due to an increase in s^i as a response to lower costs, thus the overall effect is ambiguous.

In the second stage, upstream and downstream firms choose their interaction with the intermediate market. Plugging (2.13), (2.14) and (2.16) into (2.6) and (2.8), and solving the maximization problems with respect to x^u and s^i, we obtain the reaction functions:

$$s^i = \frac{2(c_d^i - c_d^d - bx^u)}{5b} \tag{2.17}$$

$$x^u = \frac{a + c_d^i - 2c_d^d + c_u^i - 2c_u^u - 3bs^i}{6b} \tag{2.18}$$

From (2.17) we can see that if the downstream cost difference is not very big, s^i is negative and the integrated firm buys crude from the intermediate market. In this way it increases the price of the input for its rival on the downstream market and lowers the competitiveness of the pure downstream firm. However, this effect is weaker in the presence of other integrated firms on the market and in the general setting s^i can be positive as well.

Solving (2.17) and (2.18) we get the equilibrium strategies:

$$s^i = \frac{-a + 5c_d^i - 4c_d^d - c_u^i + 2c_u^u}{12b} < 0 \tag{2.19}$$

$$x^u = \frac{5a - c_d^i - 4c_d^d + 5c_u^i - 10c_u^u}{24b} \geq 0 \tag{2.20}$$

Plugging (2.19) and (2.20) back into (2.13) and (2.14), and accounting for (2.16), we get equilibrium strategies for the second stage:

$$y^i = \frac{7a - 11c_d^i + 4c_d^d - 9c_u^i + 2c_u^u}{16b} \geq 0 \tag{2.21}$$

$$y^d = \frac{a + 3c_d^i - 4c_d^d + c_u^i - 2c_u^u}{8b} \geq 0 \tag{2.22}$$

The equilibrium upstream production of the integrated firm is

$$x^i = y^i + s^i = \frac{17a - 13c_d^i - 4c_d^d - 31c_u^i + 14c_u^u}{48b} \geq 0 \tag{2.23}$$

From this equation, we can see that the crude oil extraction by the integrated firm negatively depends on the costs of its downstream rival. The decision on how much of the crude oil to extract depends on two factors, a supply of the inputs to its downstream unit and strategic play on the intermediate market in order to increase the price of the inputs for its rival. This implies that in a case of efficiency gain incurred by the independent refiner, the strategic factor prevails.

The equilibrium prices of the final good and the crude oil are given by

$$p = \frac{7a + 5c_i^d + 4c_d^d + 7c_i^u + 2c_u^u}{16} \tag{2.24}$$

$$w = \frac{5a - c_i^d - 4c_d^d + 5c_i^u + 6c_u^u}{16} \tag{2.25}$$

The last equations show that the upstream costs have a greater impact on the price of the crude than the downstream costs, while the relative of strength of the impact on the price of the final product is ambiguous.

Equilibrium profits of the firms are described by formulas that are more complicated and provided in Appendix 2. The next section analyzes the solution of the model and provides some qualitative implications.

2.3 Comparative Analysis

In the previous section, we assumed that the demand for the final product is high enough, meaning that parameter a is big relatively to the marginal costs. From the results obtained in the previous section, we can see that the integrated firm refines all its own crude, while the independent upstream firm sells some of its crude to the integrated firm ($s^i < 0$) and fully supplies the specialized downstream firm. Equations (2.24) and (2.25) show that the price of the final good is mostly determined by the production costs of the integrated firm, while the price of the crude oil is affected by the specialized firms characteristics to a greater extent, where the upstream firm costs play the key role. Figure 2.1 characterizes the relationship between the firms:

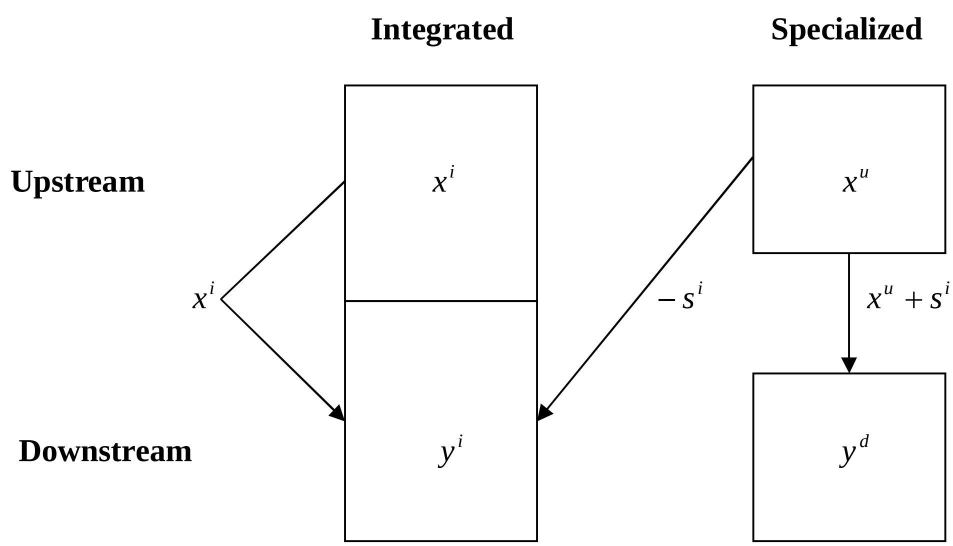

Figure 2.1: Interactions of the firms: The independent upstream firm sells crude oil to the integrated firm ($s^i < 0$)

Comparing (2.21) with (2.22) and (2.20) with (2.23), we can see that the production of the integrated firm is relatively more stable to the rivals' costs, while the specialized firms' output is seriously affected by the outside factors. From this comparison, it is clear that the independent downstream firm has the worst strategic position. In the case of equal downstream and upstream cost ($c_u^i = c_u^u$ and $c_d^i = c_d^u$), its profits account for 6.3% of overall profits in model, while the independent upstream and integrated firms have shares of 26.5% and 67.2%, respectively[3]. This means that the described industry configuration can be sustained in the presence of significant diseconomies of vertical integration. In addition, it is worth pointing out that the strategic advantage of the integrated firm decreases with the number of firms in the industry, which implies that the diseconomies of vertical integration should not be as large as it seems from the above illustration.

In addition, interesting results can be found by analyzing the effects of the outside production costs on the profitability of the specialized firms:

$$\frac{\partial \pi^u}{\partial c_i^d} = \frac{-5a + c_i^d + 4c_d^d - 5c_i^u + 10c_u^u}{192b} < 0 \qquad (2.26)$$

$$\frac{\partial \pi^u}{\partial c_d^d} = \frac{-5a + c_i^d + 4c_d^d - 5c_i^u + 10c_u^u}{48b} < 0 \qquad (2.27)$$

$$\frac{\partial \pi^d}{\partial c_i^u} = \frac{a + 3c_i^d - 4c_d^d + c_i^u - 2c_u^u}{32b} > 0 \qquad (2.28)$$

$$\frac{\partial \pi^d}{\partial c_u^u} = \frac{-a - 3c_i^d + 4c_d^d - c_i^u + 2c_u^u}{16b} < 0 \qquad (2.29)$$

These equations imply that the specialized upstream firm benefits from the production efficiency of the both downstream units; however, the effect of the pure downstream firm's costs is much stronger, while the independent downstream firm benefits just from the independent upstream firm cost reduction. Moreover, it is worse off in the case of the simultaneous upstream efficiency gain:

[3] In the case of equal costs inside the industries the values of the parameters of the model do not play any role in determining the shares of profits

$$\frac{\partial \pi^d}{\partial c_i^u} + \frac{\partial \pi^d}{\partial c_u^u} < 0 \tag{2.30}$$

Another issue that also deserves some interest is the relative specialization of the integrated firm. We measure it as the ratio of the quantity of the crude oil extracted to the quantity of the final good produced by the integrated firm:

$$\delta^i = \frac{x^i}{y^i} = 1 + \frac{s^i}{y^i} < 1 \tag{2.31}$$

$$\frac{\partial \delta^i}{\partial c_i^u} = \frac{32(-2a + 7c_i^d - 5c_d^d + 2c_u^u)}{3(7a - 11c_i^d + 4c_d^d - 9c_i^u + 2c_u^u)^2} < 0 \tag{2.32}$$

$$\frac{\partial \delta^i}{\partial c_i^d} = \frac{32(3a - 3c_d^d - 7c_i^u + 4c_u^u)}{3(7a - 11c_i^d + 4c_d^d - 9c_i^u + 2c_u^u)^2} > 0 \tag{2.33}$$

The effects of production costs on the relative specialization are of the expected signs; however, the integrated firm always refines more than it extracts. Accounting for the production levels described by (2.21) and (2.23), we can see that a drop in the production costs of each unit of the integrated firm increases the output of the both units, while the firm becomes more relatively specialized in the production stage, where this drop was incurred.

In this chapter, we analyzed the simple two-stage model of the oil industry, described the production decisions of the firms and emphasized the effects of the cost difference on the firms' behavior. It was shown that integrated firms have a superior position not just because of the absence of double marginalization, but possibility to use the market for crude oil as a strategic instrument: buying crude oil from the market increases the price of inputs for independent downstream firms and lowers their competitiveness on the market. The model also serves as a basis for the further analysis and is useful for a better understanding of the more complicated three-stage game with investment described in the next chapter.

Chapter 3

Three-Stage Model with Investment

In this chapter, we modify the basic model of the oil industry to allow the firms to invest in order to lower their production costs before the production process starts. The aim of this model is to capture various factors that affect investment decisions and explain how cost asymmetry among firms can arise even when all firms have the same technology and resources.

3.1 General Setup

As was discussed above, although vertical integrated firms have various advantages, they can suffer from managerial diseconomy and diseconomy of control, as well as worse ability to acquire new knowledge into the production process. Therefore, there is a reason to believe that the efficiency of investment can differ between intergraded and specialized firms. The model described below incorporates this reasoning.

In the first stage of the game, firms can invest, decreasing the cost of their production. The expenditures of such investments are denoted as $E^i(I_i^u, I_i^d)$, $E^u(I_u^u)$ and $E^d(I_d^d)$ for integrated, upstream and downstream firms respectively. Then the costs of production are $C^i(x^i, y^i, I_i^u, I_i^d)$, $C^u(x^u, I_u^u)$ and $C^d(y^d, I_d^d)$, where $I_i^u, I_i^d, I_u^u, I_d^d \geq 0$.

After the investment decisions are made, the basic two-stage game discussed in the previous chapter is played. The profit functions of the firms to be maximized in equilibrium are:

$$\pi^u = x^u w - C^u(x^u, I_u^u) - E^u(I_u^u) \tag{3.1}$$

$$\pi^d = y^d p(Y) - y^d w - C^d(y^d, I_d^d) - E^d(I_d^d) \tag{3.2}$$

$$\pi^i = y^i p(Y) + s^i w - C^i(y^i + s^i, y^i, I_i^u, I_i^d) - E^i(I_i^u, I_i^d) \tag{3.3}$$

This game can not be solved in the general setup, and therefore, the next section provides the solution of the specific form of the model.

3.2 The Case of Investments Downstream

In this section, we consider the case of the general model where firms can invest just into their downstream production. As well as in the basic two-stage model, we will consider just three firms and make the same assumptions about the production technology and a demand for the final good. The marginal costs of downstream production are affected by investment decisions and are $c_d^d = C_d^d - I_d^d$ and $c_i^d = C_i^d - I_i^d$, where $C_i^d \geq I_i^d \geq 0$, $C_d^d \geq I_d^d \geq 0$. The costs of these investments are assumed to take a quadratic form and are $R^d (I_d^d)^2$ and $R^d (I_i^d)^2$. In order to rule out the unrealistic corner solution, when marginal costs of production are driven to zero ($C_d^d = I_d^d$ or $C_i^d = I_i^d$), we assume that the parameter R^d is big enough, meaning that the investments are expensive. Thus, the profit functions of the firms can be written as follows:

$$\pi^u = x^u (w - c_u^u) \tag{3.4}$$

$$\pi^d = y^d (a - b(y^d + y^i)) - y^d w - y^d c_d^d - R^d (I_d^d)^2 \tag{3.5}$$

$$\pi^i = y^i (a - b(y^d + y^i)) + s^i w - y^i c_d^i - (y^i + s^i) c_u^i - R^d (I_i^d)^2 \tag{3.6}$$

The last two stages of this game are identical to the game discussed in Section 2.2, so we will proceed to the investment stage. Plugging the equilibrium production quantities and the price of the crude oil from (2.19), (2.20), (2.21), (2.22) and (2.25) into the profits functions (3.5) and

(3.6), and maximizing them with respect to I_i^d and I_d^d , we obtain the following reaction functions:

$$I_i^d = \frac{179a - 343C_i^d + 164C_d^d - 189c_i^u + 10c_u^u - 164I_d^d}{768bR^d - 343} \tag{3.7}$$

$$I_d^d = \frac{a + 3C_i^d - 4C_d^d + c_i^u - 2c_u^u - 3I_i^d}{16bR^d - 4} \tag{3.8}$$

Solving these equations for I_i^d and I_d^d, we obtain the equilibrium investment decisions:

$$I_i^d = \frac{(179bR^d - 55)a - (189bR^d - 37)c_i^u + (10bR^d + 18)c_u^u - (343bR^d - 55)C_i^d + 164bR^d C_d^d}{768(bR^d)^2 - 535bR^d + 55}, \tag{3.9}$$

if the numerator is greater than zero, and $I_i^d = 0$ otherwise.

$$I_d^d = \frac{(48bR^d - 55)a + (48bR^d + 14)c_i^u - (96bR^d - 41)c_u^u + 144bR^d C_i^d - (192bR^d - 55)C_d^d}{768(bR^d)^2 - 535bR^d + 55}, \tag{3.10}$$

if the numerator is greater than zero, and $I_d^d = 0$ otherwise.

Analyzing (3.9) and (3.10) we can see that the amount of investment negatively depends on the own ex ante production costs and positively on the rivals costs, meaning that in this setting ex ante costs difference affects ex post costs difference positively. However, we assumed that parameter a is relatively high, which implies that the integrated firm always invests more than its rival does. It has a better return on the investments, because it avoids double marginalization and has a superior strategic position, and hence, invests more. Moreover, the investment decision of the integrated firm is relatively unaffected by the independent upstream firm costs, while the specialized downstream firm puts significantly more weight on this factor.

The implication of the model described in this section is that in the absence of investment disadvantages for the integrated firm, the investment possibilities weaken the specialized downstream firm position on the market, lowering the profits of the firm. However, the independent upstream firm is an obvious winner, as it benefits from the efficiency gain of both downstream units. The effect of the downstream investment possibilities on the integrated firm is ambiguous, as it benefits from the gain in efficiency, but incurs investment expenditures. The next section expands the analysis, allowing the firms to invest into upstream production as well.

3.3 The Case of Investments into Upstream and Downstream Productions

In this section, we consider the case of the general model where firms are able to invest into their downstream and upstream productions. Again, we will consider just three firms and make the same assumptions about the production technology and a demand for the final good. The marginal costs of downstream and upstream productions are affected by the investment decision and are $c_d^d = C_d^d - I_d^d$, $c_i^d = C_i^d - I_i^d$, $c_u^u = C_u^u - I_u^u$ and $c_i^u = C_i^u - I_i^u$, where $C_i^d \geq I_i^d \geq 0$, $C_d^d \geq I_d^d \geq 0$, $C_i^u \geq I_i^u \geq 0$, $C_u^u \geq I_u^u \geq 0$. In this setup of the model, we assume that the integrated firm has worse ability to acquire new knowledge into its production processes, when investing into the both of its units[4]. It results in the higher expenditures incurred by the firm. As in the previous section the costs of the investments are assumed to take quadratic form and are $R^u (I_u^u)^2$ and $R^d (I_d^d)^2$ for the specialized firms, however, the costs incurred by the integrated firm are $R^u (I_i^u)^2 + R^d (I_i^d)^2 + R I_i^u I_i^d$, where $R^u, R^d, R > 0$. The term $R I_i^u I_i^d$ represents the investment disadvantage of the integrated firm. In order to rule out the unrealistic corner solution, when marginal costs of production are driven to zero, we assume that parameters R^d, R^u are big

[4] This means that we assume that investment disadvantages prevail over advantages of integrated firms. However, it can be questioned which effect is stronger..

enough. According to these assumptions, the profit functions of the firms take the following forms:

$$\pi^u = x^u(w - c_u^u) - R^u(I_u^u)^2 \tag{3.11}$$

$$\pi^d = y^d(a - b(y^d + y^i)) - y^d w - y^d c_d^d - R^d(I_d^d)^2 \tag{3.12}$$

$$\pi^i = y^i(a - b(y^d + y^i)) + s^i w - y^i c_d^i - (y^i + s^i)c_u^i - R^u(I_i^u)^2 - R^d(I_i^d)^2 - R\, I_i^u I_i^{d\,2} \tag{3.13}$$

The last two stages of this game are identical to the game discussed in Section 2.2, so we will proceed to the investment stage. Plugging the equilibrium production quantities and the price of the crude oil from (2.19), (2.20), (2.21), (2.22) and (2.25) into the profits functions (3.11), (3.12) and (3.13), and maximizing them with respect to I_i^d, I_i^u, I_u^u and I_d^d , we obtain the following reaction functions:

$$I_i^u = \frac{177a - 189C_i^d + 12C_d^d - 287C_i^u + 110C_u^u + (189 - 384bR)I_i^d - 12I_d^d - 110I_u^u}{768bR^u - 287} \tag{3.14}$$

$$I_u^u = \frac{5(5a - C_i^d - 4C_d^d + 5C_i^u - 10C_u^u + I_i^d + 4I_d^d - 5I_i^u)}{192bR^u - 50} \tag{3.15}$$

$$I_i^d = \frac{179a - 343C_i^d + 164C_d^d - 189C_i^u + 10C_u^u - 164I_d^d - (384bR - 189)I_i^u - 10I_u^u}{768bR^d - 343} \tag{3.16}$$

$$I_d^d = \frac{a + 3C_i^d - 4C_d^d + C_i^u - 2C_u^u - 3I_i^d - I_i^u + I_u^u}{16bR^d - 4} \tag{3.17}$$

Solving these equations, we obtain the equilibrium investment decisions, which are described by complicated equations and provided in Appendix 3.

For the sake of easier analysis, we consider simplified version of this model in order to show how the cost asymmetries can arise even in the case when the firms has access to the same technologies and resources. For this purpose we put $C_d^d = C_i^d = C^d$, $C_u^u = C_i^u = C^u$ and $R^d = R^u = \frac{R}{2}$, and analyze the cost differences between integrated and specialized firms:

$$c_i^d - c_d^d = I_d^d - I_i^d = \frac{b(a - C^d - C^u)R(6bR - 29)}{756(bR)^2 - 1054br + 315} \tag{3.18}$$

$$c_i^u - c_u^u = I_u^u - I_i^u = -\frac{b(a - C^d - C^u)R(bR + 29)}{756(bR)^2 - 1054br + 315} \tag{3.19}$$

Equations (3.18) and (3.19) show that in the presence of investment disadvantage of the integrated firm, the specialized firms can have a cost advantage over the integrated firm ex post the investment, while having the same technology and resources ex ante.

The next section presents simulations of the results this model, although we can not examine them analytically because of the complexness of the formulas.

3.4 Simulations

The equilibrium strategies of the model discussed in the previous section are described by complicated equations to evaluate them. That is why this section presents some simulations for illustrative purposes. The simulations will evaluate the impact of the parameters on the equilibrium of the model. Due to the lack of data, the values of the parameters are taken without explicit reference to the real state of the world. The strategic advantage of the integrated firm decreases with the number of firms in the industry, so we had to assign to parameter R relatively high value for the purposes of illustration. However, in the presence of more firms in the model the value of this parameter should be much smaller to get similar responses.

One of the most interesting issues to consider is the impact of parameter R, which measures the investing disadvantage of the integrated firm, on the output of the model. We put $a = 40$, $b = 1$, $C_d^d = C_i^d = 5$, $C_u^u = C_i^u = 10$, $R^d = 5$ and $R^u = 5$. The parameter R can take the values from 10 to 30. Figure 3.1 shows the impact on the investment decisions:

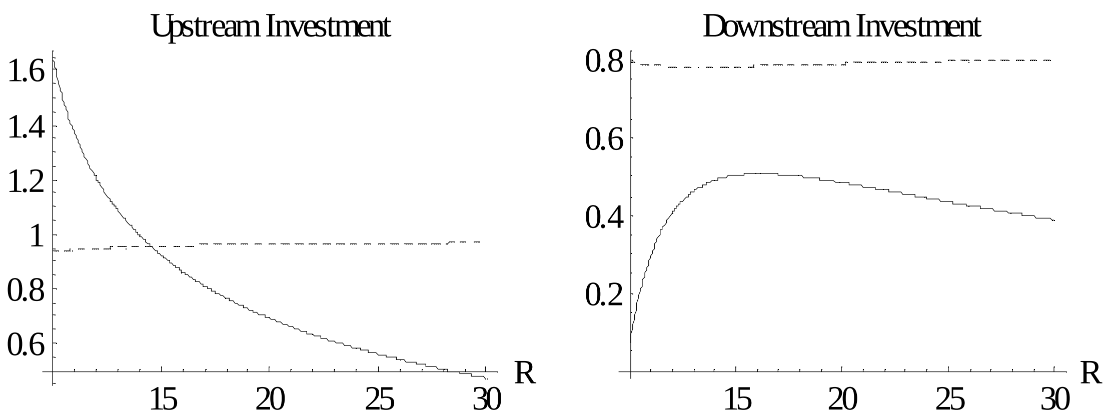

Figure 3.1: The investments of integrated (full lines) and specialized (dotted lines) firms

As we can see from the Figure 3.1, there is almost no effect on the specialized firms' investments. There is a negative response to an increase in R by the upstream investment of the integrated firm and, until some point, a positive response by the downstream investment; however, after this point the downstream investment starts to decline. This happens because lower upstream investment allows the firm to invest downstream cheaper. The next two figures show the effect on the production levels and profits of the firms, respectively:

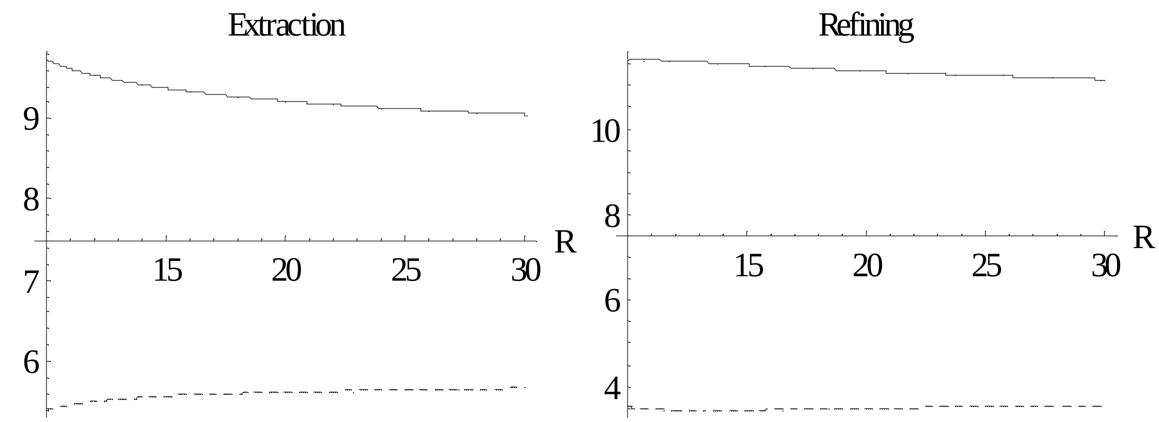

Figure 3.2: The production levels of integrated (full lines) and specialized (dotted lines) firms

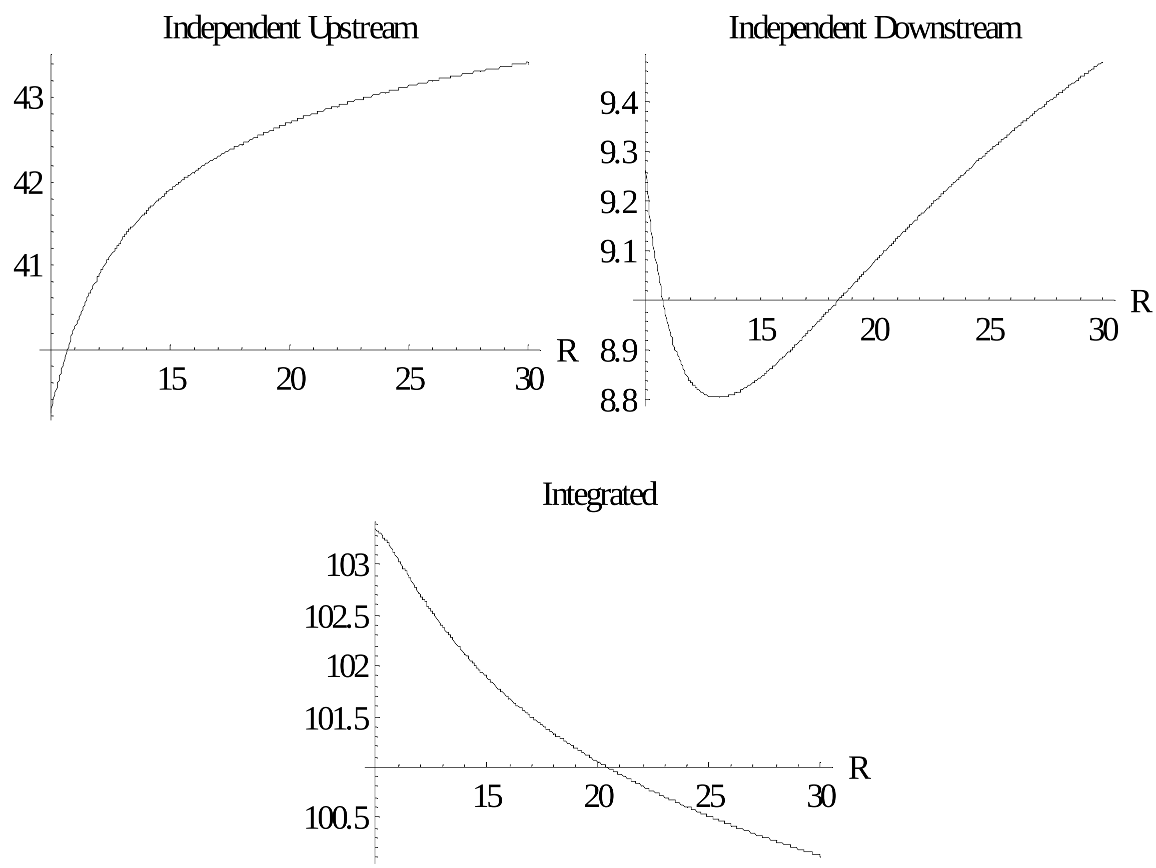

Figure 3.3: Profits of the firms

Figure 3.2 shows that the production of the specialized firms increases with R and the production of the integrated firm decreases with R. From Figure 3.3 we can observe that the profits of the independent upstream firm always depend positively on R, and the profits of the integrated firm depend negatively on R. However, the profits of the independent downstream firm can both increase or decrease. This pattern can be explained by the relationship between the downstream investment of the integrated firm and R depicted by the Figure 3.1, as the profits of the pure downstream firm negatively depend on the downstream production costs of the integrated firm.

The next simulation will illustrate the effect of upstream cost differences on the investment decision of the firms. Again, we put $a = 40$, $b = 1$, $C_d^d = C_i^d = 5$, $C_i^u = 10$, $R = 20$, $R^d = 5$ and $R^u = 5$. The ex ante costs of independent upstream firm C_u^u can take the values from 5 to 15. Figure 3.4 shows the impact on the investment decisions:

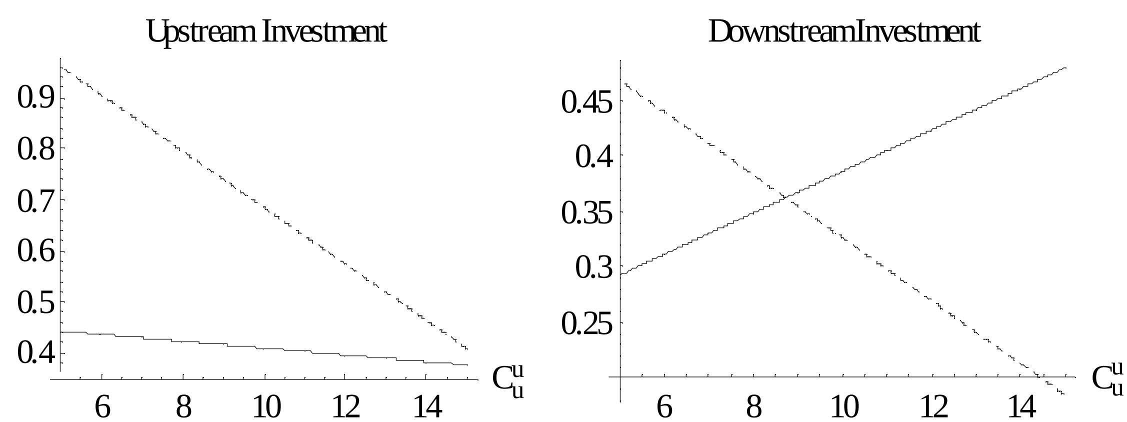

Figure 3.4: The investments of integrated (full lines) and specialized (dotted lines) firms

As we can see from this figure, the independent firms invest more than the integrated firm if the independent upstream firm has ex ante cost advantage. The integrated firm chooses to invest more downstream and less upstream as ex ante cost of the independent upstream firm grows.

From these patterns, we see that ex ante cost advantage of the pure upstream firm leads to ex post cost advantage of the independent downstream firm.

We do not present the effects of ex ante cost asymmetry on the profits and production quantities, as these effects are similar to the effects of cost asymmetry in the simpler model discussed in the Chapter 2 and can not provide any further insights.

The simulations presented in this section have illustrated the effects of some factors on the investment decisions of the firms. The patterns obtained show that downstream cost asymmetry can arise from other factors than production technology and available resources, namely, from the corporate structure of the industry. Nowadays big national companies are mostly upstream players and clearly have cost advantage over integrated multinationals. There are reasons to believe that integrated firms can have an investment disadvantage in terms of costs. So applying these issues to the results from the illustrations, we can partially explain the existence and profitability of pure downstream firms.

Conclusion

The aim of this thesis was to build a model of the partially integrated oil industry, with the strict division of the production process into upstream and downstream stages. The model took the form of a static non-cooperative game with the three types of players: pure upstream, pure downstream and integrated firms. The focus of the analysis was on the differences in incentives and optimal behavior between the types of the firms, with special emphasis on the investment decisions and production cost asymmetry. In order to solve the model, we made the simplifying assumptions, which did not distort the qualitative implications of the model significantly. However, we accounted for possible distortions compared to more general specifications.

The simple two-stage model of the oil industry was analyzed in order to evaluate the substantial differences in strategic positions between the types of firms and describe their interaction. The analysis showed that integrated firms have not just the advantage of avoiding double marginalization but can use the market of crude oil as a strategic instrument: buying crude from the market increases the price of inputs for independent downstream firms and lowers competitiveness in the downstream industry. Substantial emphasis was put on the effects of production costs on the output of the model, in order to build a basis for the model of the oil industry with investment possibilities. The results of the two-stage model made it easier to understand the impact of cost-reducing investments on the industry.

The outcome of the three-stage model could be described by too complicated formulas to evaluate them analytically. That is why simulations were used in order to illustrate the effects of the industry characteristics on the investment and production decisions made by the firms. The patterns obtained show that downstream cost asymmetry can arise from other factors than production technology and available resources, namely, from the corporate structure of the industry. The key assumption in the setup of the model was that integrated firms have investment disadvantage compared to specialized ones in terms of cost of investment. Moreover, nowadays big national companies are mostly upstream oriented and clearly have the cost advantage over integrated multinationals. The simulations showed that either of these issues can lead to a downstream production cost asymmetry. This can be related to the fact that the best performing oil companies recently seem to be the pure play upstream or downstream companies.

Lastly, it must be stated that the model has considerable diversions from reality. Most notably, it concerns the functional form specifications, the functioning of the crude oil market and a small number of firms are involved in the model. However, these simplifications were necessary to conduct the analysis. This means that there is room for more complicated research on this question, which would require complex numerical simulations. On the other hand, empirical studies of the question deserve a great interest, although there is a data problem contracting the scope of a possible analysis. Nevertheless, this thesis contributes to the understanding of the investment incentives of firms, provides insights into the effects and origins of production cost asymmetry in a vertical integrated industry and can be used as a framework for further analysis of the oil industry and other natural resource industries.

Appendices

Appendix 1: Descriptive Tables

Table 1. Largest oil-producing companies ranked by estimated oil production (mb/d)

	1972			2000		
Rank	*Company*	*Production*	*Share*	*Company*	*Production*	*Share*
1	Exxon	5.0	10.8%	**Saudi Aramco**	8.8	11.7%
2	**BP**	4.7	10.1%	**NIOC (Iran)**	3.8	5.0%
3	Shell	4.2	9.0%	**PEMEX (Mexico)**	3.5	4.6%
4	Texaco	3.8	8.2%	**PDVSA (Venezuela)**	2.9	3.9%
5	Chevron	3.2	7.0%	**INOC (Iraq)**	2.6	3.4%
6	Gulf	3.2	7.0%	ExxonMobil	2.6	3.4%
7	Mobil	2.3	5.0%	Shell	2.3	3.0%
8	**Former Planned Economies**	1.3	2.8%	**CNPC (China)**	2.1	2.8%
9	**CFP (Total)**	1.0	2.1%	BP	1.9	2.6%
10	**Sonatrach (Algeria)**	0.9	2.0%	**KPC (Kuwait)**	1.9	2.5%
11	Amoco	0.8	1.8%	**ADNOC (Abu Dhabi)**	1.8	2.4%
12	Arco	0.7	1.4%	Lukoil	1.5	2.1%
13	Du Pont	0.6	1.3%	**NOC (Libya)**	1.5	2.0%
14	USX (Marathon)	0.5	1.0%	TotalFinaElf	1.4	1.9%
15	**PEMEX (Mexico)**	0.4	1.0%	**Petrobras**	1.3	1.8%
16	Occidental	0.4	1.0%	**Pertamina (Indonesia)**	1.2	1.6%
17	Getty	0.4	1.0%	**NNPC (Nigeria)**	1.2	1.6%
18	Sun	0.4	0.8%	Chevron	1.2	1.5%
19	Unocal	0.4	0.8%	**Sonatrach (Algeria)**	1.0	1.3%
20	Phillips	0.3	0.7%	Yukos	1.0	1.3%

Note: Companies with state participation are in bold.
Source: *IEA World Energy Outlook*, 2001 Insights in Glomsrod, S. and Lindhol, L. (2004), *The Petroleum Business Environment. A reader's digest*, Statistics Norway Research Department

Table 2. Output, refining capacities and reserves of top 46 integrated oil producers (1993)

Company	Oil production (1,000 b/d)		Refining capacity (1,000 b/d)		Refining/production		Oil Reserves (mill. bbls)	
	production	rank	refining	rank	ref./prod.	rank	reserves	rank
Saudi Aramco**	8,047	1	1,750	7	0.217	42	261,203	1
NIOC**	3,425	2	1,081	11	0.316	38	92,860	4
Pemex**	3,140	3	1,500	9	0.478	32	50,766	7
CNPC**	2,829	4	300	35	0.106	46	13,599	9
PDV**	2,563	5	2,061	4	0.804	29	64,450	6
RD/Shell	2,133	6	4,197	1	1.968	14	9,124	12
KPC**	1,881	7	670	19	0.356	37	96,500	3
Exxon	1,667	8	3,972	2	2.383	9	6,564	13
NNPC**	1,524	9	400	32	0.262	39	12,585	10
Luk Oil**	1,374	10	556	26	0.405	36	2,801	23
Libya NOC**	1,361	11	570	25	0.419	34	22,800	8
BP	1,242	12	1,907	6	1.535	17	6,537	14
Sonatrach**	1,147	13	474	30	0.683	31	9,200	11
Adnoc**	1,055	14	193	40	0.183	43	64,452	5
Chevron	950	15	2,029	5	2.136	12	4,185	16
Mobil	838	16	2,100	3	2.506	8	3,343	20
Texaco	728	17	1,588	8	2.181	11	2,685	24
Pertamina**	708	18	783	16	1.106	24	5,760	15
Arco	684	19	522	29	0.763	30	2,465	26
Amoco	678	20	1,007	13	1.485	18	2,223	28
Petrobas*	668	21	1,288	10	1.928	15	3,800	17
INOC	619	22	550	27	0.889	27	100,000	2
Elf Aquitaine*	619	23	756	17	1.221	21	2,535	25
ENI**	536	24	1,019	12	1.901	16	3,463	19
EGPC**	502	25	523	28	1.042	25	3,500	18
PDO**	466	26	80	43	0.172	44	2,820	22
Statoil**	449	27	195	39	0.434	34	2,023	30
Conoco	434	28	579	22	1.334	19	1,694	32
Total	430	29	910	14	2.116	13	2,844	21
OGPG**	390	30	63	45	0.162	45	2,445	27
Philips	362	31	355	33	0.981	26	1,037	34
Petronas**	325	32	75	44	0.231	41	1,813	31
YPF**	299	33	354	34	1.184	23	1,005	35
Ecopetrol**	288	34	248	38	0.861	28	2,087	29
Unocal	246	35	296	36	1.203	22	754	37
Amerada Hess	215	36	575	24	2.674	7	670	38
BHP	205	37	95	42	0.463	33	666	39
Norsk Hydro*	190	38	45	46	0.237	40	540	40
Rapsol*	162	39	752	18	4.642	5	412	42
Marathon	156	40	579	22	3.712	6	842	36
Petro-Canada*	121	41	283	37	2.339	10	389	43
Petroecuador**	120	42	148	41	1.233	20	1,500	33
Petrofina	92	43	611	21	6.641	4	530	41
Sun	38	44	670	19	17.631	3	55	44
Coastal	14	45	473	31	33.785	2	29	46
Nippon Oil	9	46	810	15	90.000	1	40	45

Note: The asterisk indicates that the company is partly state-owned and the double asterisk that it is fully state-owned.
Source: *Petroleum Intelligence Weekly - Special Supplement Issue*, December 12, 1994 in Gaudet et al, 1999, Upstream-Downstream Specialization by Integrated Firms in a Partially Integrated Industry, *Review of Industrial Organization*, Volume 14, Number 4 / June, 1999

Appendix 2: Profits of the Firms in the Basic Two-Stage Game

Plugging the results from (2.19-25) back into the profit functions (2.6), (2.7) and (2.8) we obtain the equilibrium profits of the firms:

$$\pi^u = \frac{(5a - c_i^d - 4c_d^d + 5c_i^u - 10c_u^u)^2}{384b}$$

$$\pi^d = \frac{(a + 3c_i^d - 4c_d^d + c_i^u - 2c_u^u)^2}{64b}$$

$$\pi^i = \frac{1}{768b}\Big(127a^2 + 343(c_i^d)^2 + 112(c_d^d)^2 + 287(c_i^u)^2 - 2a(179c_i^d - 52c_d^d + 177c_i^u - 50c_u^u) + c_i^d(378c_i^u - 328_d^d - 20c_u^u) - 24c_d^d c_i^u - 80c_d^d c_u^u - 220c_i^u c_u^u + 60(c_u^u)^2\Big)$$

Appendix 3: Equilibrium Investment Decisions In the Three-Stage Model with Investment Upstream and Downstream

Solving the equations (3.14-17), we obtain the following equilibrium investment decisions:

$I_i^u = \bar{I}_i^u$ if $\bar{I}_i^u > 0$ and $I_i^u = 0$ otherwise.

$I_u^u = \bar{I}_u^u$ if $\bar{I}_u^u > 0$ and $I_u^u = 0$ otherwise.

$I_i^d = \bar{I}_i^d$ if $\bar{I}_i^d > 0$ and $I_i^d = 0$ otherwise.

$I_d^d = \bar{I}_d^d$ if $\bar{I}_d^d > 0$ and $I_d^d = 0$ otherwise.

Where $\bar{I}_i^u, \bar{I}_u^u, \bar{I}_i^d$ and $\bar{I}_d^d$ are:

$$\bar{I}_i^u = \frac{(2R^d(-320 + 725bR^d + 960bR^u - 2124b^2R^dR^u) + R(115 - 575bR^d - 660bR^u + 2148b^2R^uR^d))}{D}a + \frac{R(-115 + 1075bR^d + 660bR^u - 4116b^2R^dR^u) + 2R^d(145 - 625bR^d - 540bR^u + 2268b^2R^dR^u)}{D}C_i^d + \frac{R^d(-175 - 24b^2(41R - 6R^d)R^u + 10b(25R + 10R^d + 42R^u))}{D}C_d^d +$$

$$\frac{280R^{u}+R^{d}(640-3664bR^{u})+2b(R^{d})^{2}(-725+3444bR^{u})+R(-115+575bR^{d}+444bR^{u}-2268b^{2}R^{d}R^{u}}{D}C_{i}^{u}+$$

$$\frac{4(-35+15b^{2}(R-22R^{d})R^{d}+b(27R+218R^{d}))R^{u}}{D}C_{u}^{u},$$

$$\bar{I}_{u}^{u}=\frac{5(R(23-163bR^{d})+24bR^{2}(-1+5bR^{d})+2R^{d}(-64+145bR^{d}+144bR^{u}-240b^{2}R^{d}R^{u}))}{D}a+$$

$$\frac{5(-24bR^{2}(-1+bR^{d})+R(-23+119bR^{d})+2R^{d}(29-77bR^{d}-48bR^{u}+48b^{2}R^{d}R^{u}))}{D}C_{i}^{d}+$$

$$\frac{5R^{d}(-35+b(-22R+68R^{d}+96R^{u})+48b^{2}(R^{2}-R^{u}R^{d}))}{D}C_{d}^{d}+$$

$$\frac{5(R(29-77bR^{d})+24bR^{2}(-1+5bR^{d})-2(23-167bR^{d}+240b^{2}(R^{d})^{2})R^{u})}{D}C_{i}^{u}+$$

$$\frac{5(R(26-120bR^{d})+24bR^{2}(-1+5bR^{d})-23R^{u}-5b(R^{d})^{2}(-29+96bR^{u})+R^{d}(-64+311bR^{u}))}{D}C_{u}^{u},$$

$$\bar{I}_{i}^{d}=\frac{R(145-725bR^{d}-540bR^{u}+2124b^{2}R^{d}R^{u})-6R^{u}(85+716b^{2}R^{d}R^{u}-5b(57R^{d}+44R^{u}))}{D}a+$$

$$\frac{30R^{u}(17-44bR^{u})+R(-145+625bR^{d}+549bR^{u}-2268b^{2}R^{d}R^{u})+R^{d}(350-4110bR^{u}+8232b^{2}(R^{u})^{2})}{D}C_{i}^{d}+$$

$$\frac{R^{d}(175-24b^{2}(3R-82R^{u})R^{u}-50b(R-24R^{u}))}{D}C_{d}^{d}+$$

$$\frac{R(-145+725bR^{d}+852bR^{u}-3444b^{2}R^{d}R^{u})+2R^{u}(115-575bR^{d}-444bR^{u}+2268b^{2}R^{u}R^{d})}{D}C_{i}^{u}+$$

$$\frac{4R^{u}(-35+b(39R+70R^{d}+54R^{u})+b^{2}(-165RR^{d}+30R^{d}R^{u}))}{D}C_{u}^{u},$$

$$\bar{I}_{d}^{d}=\frac{288b^{2}R^{2}R^{u}+R(145-816bR^{u})+6R^{u}(-85-192b^{2}R^{d}R^{u}+4b(29R^{d}+55R^{u}))}{D}a+$$

$$\frac{R(115-168bR^{u})+48bR^{2}(-5+18bR^{u})-2R^{d}(145-984bR^{u}+1728b^{2}(R^{u})^{2})}{D}C_{i}^{d}+$$

$$\frac{15R^u(17-44bR^u)-24bR^2(-5+24bR^u)+2R(-65+246bR^u)+2R^d(145-1332bR^u+2304b^2(R^u)^2)}{D}C_d^d+$$

$$\frac{288b^2R^2R^u+R(-145+504bR^u)-2R^u(-115+168bR^u+576b^2R^dR^u)}{D}C_i^u+$$

$$\frac{4R^u(-35+b(-39R+87R^d+123R^u)+72b^2(R^2-4R^dR^u))}{D}C_u^u \text{ and}$$

$$D=2\Big(15R^u(17-44bR^u)+R(-130+600bR^d+492bR^u-2268b^2R^dR^u)^d)$$

$$+24bR^2(5-25bR^d-24bR^u+96b^2R^uR$$

$$+b(R^d)^2(-725+5844bR^u-9216b^2(R^u)^2)+R^d(320-3387bR^u+6420b^2(R^u)^2)\Big)$$

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