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Gérard Gaudet, Ngo Van Long,
Antoine Soubeyran

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Upstream-Downstream Specialization by Integrated Firms in a Partially Integrated Industry*

Gérard Gaudet[†], *Ngo Van Long*[‡], *Antoine Soubeyran*[§]

Résumé / Abstract

On s'intéresse à la détermination du degré de spécialisation amont-aval d'une industrie partiellement intégrée. La situation est modélisée de sorte à pouvoir prendre en compte des différences persistantes de coût de production entre firmes en amont, ce qui est typique de plusieurs industries de ressources naturelles. Le modèle permet de faire ressortir les rôles respectifs des considérations stratégiques et des considérations de coût dans la détermination de l'interaction d'une firme intégrée avec le secteur non intégré de l'industrie et, de ce fait, la détermination de sa spécialisation relative amont-aval. Des faits stylisés tirés de l'industrie pétrolière mondiale viennent illustrer le type de comportement auquel on peut s'attendre dans un tel contexte.

We propose a simple model of a partially integrated industry which explicitly takes into account persistent production cost differences across upstream firms, such as one might observe in natural resource industries. The model allows us to highlight the respective roles of strategic considerations in the determination of an integrated firm's interaction with the non-integrated sector of the industry and, in the end, on its relative upstream-downstream specialization. Stylized facts from the world oil industry are used to illustrate the type of behaviour one might expect in this context.

Mots Clés : Firmes intégrées, spécialisation, interactions stratégiques

Keywords : Integrated Firms, Specialization, Strategic Interactions

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† Université Laval, GREEN & CIRANO

‡ McGill University & CIRANO

§ GREQAM & Université d'Aix-Marseille II

1 Introduction

Studies of vertical integration have typically modelled the integration decision as a dichotomic decision where, although some firms may be integrated and some not, all integrated firm behaves in the same way, as do all non-integrated firm[1]. For many industries this is a reasonable simplification, since there is usually no reason to believe that either upstream or downstream cost asymmetries can persist in the long run and there is therefore no a priori justification for the integrated firms not to behave identically.

However, if there are persistent cost differences amongst firms, then the relative upstream-downstream specialization decision of each integrated firm should depend on its upstream-downstream cost advantage. Natural resource industries provide notable examples of such situations, for in those industries upstream costs are exogenously determined by nature and usually differ between producers. It is well known for instance that crude oil production costs — both the physical extraction costs and the opportunity cost due to the fixed reserve size — vary widely across producers. One would expect those inherent cost asymmetries to result in asymmetric behavior on the part of integrated oil companies. The stylized facts from the oil industry discussed in the next section seem to confirm those expectations.

The purpose of this paper is to analyse the effect of upstream cost asymmetries on the behavior of integrated firms. We propose a simple model of a partially integrated industry which explicitly takes into account these upstream cost asymmetries. The model allows us to highlight the respective roles of strategic considerations and of cost considerations in the determination of an integrated firm's interaction with the non-integrated sector of the industry and, in the end, on its relative upstream-downstream specialization.

To fix the ideas, we will refer to the upstream stage as that of crude oil production and to the downstream stage as that of oil refining. The model is however relevant to any partially

[1]See for instance the papers by Bonanno and Vickers (1988), Gaudet and Long (1995), Hart and Tirole (1990), Ordover, Saloner and Salop (1990), Salinger (1988), as well as the survey by Perry (1989).

integrated two-stage natural resource industry[2] or, for that matter, any industry where upstream production cost differences are important and persistent, for whatever reason.

Before going on to discuss the model and its assumptions, we take a brief look in the next section at some stylized facts taken from the world oil industry. These facts illustrate the type of behaviour one can expect from integrated firms in a vertically related industry with important upstream cost differences across firms. We discuss the model and its assumptions in section 3 and present the equilibrium strategies in section 4. In section 5, we characterize the strategic and cost elements of an integrated firm's behaviour and derive from the model some predictions as to the effects of costs asymmetries which may be easily related to the facts presented in section 2. We offer a brief conclusion in section 6.

2 Some stylized factual evidence

As already noted in the introduction, differentiated upstream costs are common in many natural resource industries. This is well illustrated by the world oil industry. Although reliable published data on costs by individual oil producers are scarce, it is widely acknowledged that upstream costs differ greatly across producers[3].

One imperfect indicator of some of the costs for which reasonably reliable micro-data is available is oil reserves. In many cases, the larger the reserves, the easier can the oil be extracted. Hence the operating costs will often be inversely related to the size of reserves. Just as important, however, is the fact that in an oligopolistic world the larger a firm's reserves the lower its opportunity costs, in terms of foregone future profits, of extracting the marginal barrel today rather than leaving it for future extraction[4]. For lack of direct

[2] The model simplifies the non renewable resource reality however, in that it neglects the dynamic aspects of non renewable resource extraction. We believe nonetheless that the static model we propose is helpful in gaining some insight into the problem and that this insight might be overshadowed in a dynamic model which would explicitly take into account the non renewability constraints.

[3] See for instance Adelman and Shahi (1989) who provide estimates of development-operating costs for a number of oil producing nations (not companies) for the period 1955 to 1985.

[4] This inverse relationship between a firm's reserves and its opportunity cost of extraction would of course

measures of upstream costs, let us therefore use reserves as a rough indicator of at least an important part of those costs[5].

Table 1 shows the data for oil production, refining capacity and oil reserves for the top forty-six integrated oil producers in 1993, ranked by upstream production. Quite obviously, reserves vary considerably, as do oil outputs and refining capacities. The third column of Table 1 shows the ratio of refining capacity to upstream production (the second column divided by the first column). This variable can be considered a measure of the degree of specialization of each company between upstream and downstream production. It also varies greatly across firms.

In Figures 1 through 3, we have plotted the individual company ranks for respectively upstream oil production, refining capacity and the ratio of refining capacity to production against the ranks for reserves. In each case, a simple linear fit is drawn through the data, as a crude indicator of the direction of the relationship between the two variables. It appears clearly from Figure 1 that the company with the larger reserves — and hence presumably the lower upstream cost — also tends to have the greater upstream production[6]. Figure 2 shows that a similar relationship holds for downstream production: the company with the lower upstream cost tends to have the larger downstream production. However, as is apparent from Figure 3, the company with the lower upstream cost will tend to have the lower ratio of downstream to upstream production. This is true even though it has greater upstream and downstream production than a company with a higher upstream costs. The implication is

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not hold in a competitive market, where firms are price takers. In such a world, a redistribution of reserves would not change the equilibrium extraction paths. But in a duopoly, for instance, the firm with the higher reserves assigns it a lower shadow value in equilibrium and redistributing reserves in its favor increases its shadow value and decreases that of the other firm (see Gaudet and Long (1994)). A redistribution of reserves then matters because of the anticipated monopoly stage. This easily extends to an n-firm non renewable resource oligopoly.

[5]Adelman *et al.* (1991) estimate the value of a barrel of oil in the ground, based on data for the United States, to be on average roughly half of the wellhead price net of operating cost, royalties, severance taxes and excise taxes.

[6]It may in fact be considered almost a truism that upstream production should be negatively related to upstream production costs. In that sense then, Figure 1 could be viewed as simply a confirmation that reserves may not be a bad indicator of costs.

that the integrated firm with the lower upstream production costs will tend to be relatively more specialized in upstream production. This implication is drawn without any observations on downstream costs. Unlike for upstream costs however, there is no a priori reason to believe that, in the long run, those costs would differ very much across firms[7].

In the following section, we propose a theoretical model of a partially integrated industry which retains the essential elements necessary to provide some predictions and explanations for the type of behaviour one might expect from firms operating in a context similar to the one just described. As we will see, these are consistent with the above stylized facts.

3 The model

Consider two vertically related industries composed of a set $N_u = \{1, 2, \ldots, n_u\}$ of upstream producers — the crude oil producers — and a set $N_d = \{1, 2, \ldots, n_d\}$ of downstream producers — the oil refiners. An integrated firm is one that controls the production of an upstream-downstream pair and maximizes their joint profit. Let m denote the number of such integrated firms. Obviously $m \leq min\{n_u, n_d\}$. We will assume $n_u \leq n_d$ and hence $m \leq n_u$. We will denote by $I_u = \{i \in N_u \mid i \text{ is integrated}\}$ the set of integrated upstream producers and by $J_u = \{j \in N_u \mid j \text{ is not integrated}\}$ the set of non integrated upstream producers. Similarly $I_d = \{i \in N_d \mid i \text{ is integrated}\}$ and $J_d = \{j \in N_d \mid j \text{ is not integrated}\}$ will denote respectively the set of integrated and of non-integrated downstream firms.

Downstream producers simply transform one unit of crude oil into one unit of refined product. We will assume that they can all do so at the same constant marginal cost which, for simplicity, we will take to be zero. Thus the only cost of producing a unit of refined product is the cost of a unit of crude oil. Upstream oil production costs will be assumed to vary across producers. The constant marginal cost of oil producer $k \in N_u$ will be denoted

[7] Of the forty-six companies retained in Table 1, twenty-two are fully state-owned and five are partly state-owned. However, Figures 1 through 3 look much the same if we restrict attention to the twenty-four firms which are publicly traded.

c_k. Since downstream producers are identical, we may assume without loss of generality that the integrated upstream producer $k \in I_u$ is paired with the downstream refiner $k \in N_d$ and we may therefore write $I_u = I_d = I$.

It will be convenient to denote by y_i and by y_j the quantity refined by respectively the integrated firm $i \in I$ and the non-integrated refiner $j \in J_d$. Similarly, x_i and x_j will represent the upstream oil production of respectively the integrated firm $i \in I$ and the non-integrated producer $j \in J_u$. The variable $s_i = x_i - y_i$ will capture integrated firm i's interrelation with the market for crude oil. If s_i is positive, then integrated firm i refines less than its downstream oil production and supplies the rest, through the crude oil market, to the non-integrated refining sector and the refining division of other integrated firms that wish to refine more than they produce; if s_i is negative, then it refines more than its own production of crude, its refining division being supplied the rest, through the crude oil market, by the non-integrated crude oil producers and the integrated firms that wish to refine less than they produce.

We will denote by p the market price of the refined product and assume the market demand to be linear, given by $Y = \beta - p$, where $Y = \sum_{k \in N_d} y_k$. The equilibrium production decisions are viewed as the result of a two-stage game. In the last (downstream) stage, firms compete in quantities to simultaneously determine y_i $(\forall i \in I)$ and y_j $(\forall j \in J_d)$, given the market demand for the refined product. In doing so they act somewhat as followers, taking as given the market price of crude oil, which we will denote w. Their equilibrium decisions therefore yield the derived market demand for crude oil as an input in the refining process. In the upstream stage, oil producers also compete à la Cournot to simultaneously determine s_i $(\forall i \in I)$ and x_j $(\forall j \in J_u)$, taking as given the derived demand schedule for crude oil expected to result from the downstream stage refining decisions.

At first thought, it might seem that an integrated firm would never wish to buy crude oil from the crude oil market at a price which is not less than its own cost of producing it, and therefore that s_i could be restricted to being positive. There are two potential reasons, to be further clarified in the next section, why this is not the case. First, as already noted, some integrated firms may have a cost disadvantage in crude oil production over other integrated firms and may therefore wish to specialize, relatively speaking, in refining. Second, and depending on the importance of the non-integrated versus the integrated sectors, all integrated firms may find it profitable to buy from the crude oil market if in doing so they can contribute to increasing the price of crude and hence the input cost of their dowstream rivals, thereby making the refining industry less competitive[8].

4 The equilibrium strategies

Since we seek a subgame perfect equilibrium, we first solve for the downstream refining decisions. In the downstream stage, an integrated firm chooses y_i, the quantity to refine, in order to maximize

$$(\beta - Y)y_i - c_i y_i + (w - c_i)s_i \tag{1}$$

which is the joint profit generated by its upstream and downstream divisions. However, what matters at this stage for an integrated firm is really its profits from the refining operation, since s_i is an upstream decision, already determined.

The profit of a non-integrated refiner, on the other hand, is given by

$$(\beta - Y)y_j - wy_j \tag{2}$$

which it wishes to maximize with respect to y_j.

Since w is taken as given by each refiner and since each is assumed to behave à la Cournot

[8]Such raising rivals' costs equilibrium strategies when upstream costs are identical, and therefore all integrated firms behave identically, are analyzed in more detail, with explicit examples being provided, in Gaudet and Long (1995).

in determining y_i and y_j, the set of first-order conditions will be

$$\begin{aligned} \beta - 2y_i - Y_i &= c_i \quad \forall i \in I \qquad (3) \\ \beta - 2y_j - Y_j &= w \quad \forall j \in J_d \qquad (4) \end{aligned}$$

where $Y_i = Y - y_i$ and $Y_j = Y - y_j$. Letting $C^I = \sum_{i \in I} c_i$, the solution to (3) and (4) can be written

$$\begin{aligned} y_i &= \frac{\beta + C^I}{n_d + 1} + \frac{n_d - m}{n_d + 1} w - c_i \quad i \in I \qquad (5) \\ y_j &= \frac{\beta + C^I}{n_d + 1} - \frac{m + 1}{n_d + 1} w \quad j \in J_d. \qquad (6) \end{aligned}$$

from which we get

$$Y = \frac{n_d \beta - C^I + (n_d - m) w}{n_d + 1}. \qquad (7)$$

Substituting into the inverse demand, we find that the price of the refined product as a function of the still to be determined market price for crude oil, w, is

$$p = \frac{\beta + C^I}{n_d + 1} + \frac{n_d - m}{n_d + 1} w. \qquad (8)$$

In order for the market for crude oil to be in equilibrium, we must have

$$\sum_{j \in J_d} y_j = \sum_{i \in I} s_i + \sum_{j \in J_u} x_j.$$

After substituting for the y_j's from (6) we find that the derived inverse market demand for the upstream crude oil is given by

$$w = \frac{1}{m + 1} \left[\beta + C^I - \frac{n_d + 1}{n_d - m} \left(S^I + X^{J_u} \right) \right]. \qquad (9)$$

where $S^I = \sum_{i \in I} s_i$ and $X^{J_u} = \sum_{j \in J_u} x_j$.

Consider now the upstream stage. At that stage, oil producers face the inverse market demand (9) in deciding how much oil to put on the market. In the case of an integrated firm this consists in choosing s_i, which gives its net position vis à vis the market. In doing so it will aim at maximizing the joint profit from both its upstream and downstream position, that is

$$(p - c_i)y_i + (w - c_i)s_i, \tag{10}$$

where now y_i, p and w are given respectively by (5), (8) and (9). A non-integrated upstream firm, on the other hand, determines x_j, its total production of crude oil, in order to maximize the profit from this single operation, which is simply

$$(w - c_j)x_j \tag{11}$$

with w given by (9).

The equilibrium to this quantity competition à la Cournot is provided by the solution to the set of first-order conditions

$$\left[(p - c_i)\frac{\partial y_i}{\partial w} + y_i \frac{\partial p}{\partial w}\right] \frac{\partial w}{\partial s_i} + w + s_i \frac{\partial w}{\partial s_i} = c_i \quad \forall i \in I \tag{12}$$

$$w + x_j \frac{\partial w}{\partial x_j} = c_j \quad \forall j \in J_u, \tag{13}$$

where, from (5),(8) and (9),

$$\frac{\partial y_i}{\partial w} = \frac{\partial p}{\partial w} = \frac{n_d - m}{n_d + 1}$$

and

$$\frac{\partial w}{\partial s_i} = \frac{\partial w}{\partial x_j} = -\frac{n_d + 1}{(m+1)(n_d - m)}.$$

As is shown in the Appendix, the solution to (12) and (13) may be written

$$s_i = \frac{m-1}{A}\left[\frac{\beta + C^I}{m+1} - c_i\right] - \frac{B}{mA}(S^I + X^{J_u}), \quad i \in I \tag{14}$$

$$x_j = \frac{m+1}{A}\left[\frac{\beta + C^I}{m+1} - c_j\right] - (S^I + X^{J_u}), \quad j \in J_u \tag{15}$$

and

$$S^I + X^{J_u} = \frac{E+F}{(n_u - m + 1)A + B} \tag{16}$$

where

$$\begin{aligned} A &= \frac{n_d + 1}{n_d - m} \\ B &= \frac{m(n_d+1}{n_d - m} - \frac{2m}{m+1} \\ E &= \frac{m(m-1)}{m+1}\left(\beta - \frac{C^I}{m}\right) \\ F &= (n_u - m)\left(\beta - \frac{C^I}{m}\right) + (m+1)\left[\frac{n_u - m}{m}C^I - C^{J_u}\right]. \end{aligned}$$

and $C^{J_u} = \sum_{j \in J_u} c_j$.

Eliminating w by substituting from (9) into (5) and (6), we may write the equilibrium productions of the refined product

$$y_i = \frac{\beta + C^I}{m+1} - \frac{S^I + X^{J_u}}{m+1} - c_i, \quad i \in I \tag{17}$$

$$y_j = \frac{S^I + X^{J_u}}{n_d - m}, \quad j \in J_d. \tag{18}$$

Using (14) and (17) we also verify that the equilibrium production of crude oil by integrated firm i is

$$x_i = s_i + y_i$$

$$= \left(1+\frac{m-1}{A}\right)\left(\frac{\beta+C^I}{m+1}-c_i\right)-\left(\frac{1}{m+1}-\frac{B}{mA}\right)\left(S^I+X^{J_u}\right), \quad i \in I. \qquad (19)$$

5 Some effects of cost asymmetries

The equilibrium solution just derived can now be used to characterize the effect of upstream cost differences on the behavior of integrated firms. To do this, consider two integrated firms, say firms i and i' both elements of I, that differ only by their upstream cost of production. We can immediately establish from (19) and (17) that

$$\begin{aligned} x_i - x_{i'} &= \frac{(n_d-m)(m-1)+n_d+1}{n_d+1}(c_{i'}-c_i), \quad i,i' \in I \\ y_i - y_{i'} &= c_{i'}-c_i, \quad i,i' \in I \end{aligned}$$

and hence

$$\begin{aligned} \text{sign}[x_i - x_{i'}] &= -\text{sign}[c_i - c_{i'}], \quad i,i' \in I \\ \text{sign}[y_i - y_{i'}] &= -\text{sign}[c_i - c_{i'}], \quad i,i' \in I. \end{aligned}$$

Therefore, not too surprisingly, the lower the cost of production of crude oil of an integrated firm, the more of it will produce. Since it has access to a relatively cheap source of input, it will also refine a greater quantity than its higher cost rivals.

Of particular interest is the relative specialization of the two firms. As a measure of this, consider the ratio of the quantity of oil refined to the quantity of crude oil produced by an integrated firm:

$$\tau_i = \frac{y_i}{x_i} = 1 - \frac{s_i}{x_i}.$$

Then, at equilibrium,

$$\tau_i - \tau_{i'} = \frac{x_i s_{i'} - x_{i'} s_i}{x_i x_{i'}} = \frac{(m+1)(S^I + X^{J_u})(c_i - c_{i'})}{(n_d+1) x_i x_{i'}}$$

and

$$\mathrm{sign}[\tau_i - \tau_{i'}] = \mathrm{sign}[c_i - c_{i'}], \quad i, i' \in I.$$

This means that although it produces more crude oil and refines a greater quantity of it, the integrated firm that has the lower upstream cost will refine less relative to its own crude production. The reason is that although the lower upstream cost gives it an absolute advantage in both crude oil production and refining compared to its higher cost integrated rivals, it also gives it a comparative advantage in upstream crude oil production. It will therefore tend to specialize more in crude oil production than its higher costs rivals. Hence the lower τ_i.

The equilibrium determination of τ_i is in fact somewhat more subtle than might appear at first sight, since both strategic and cost considerations intervene in the equilibrium determination of s_i. To see this, rewrite s_i as

$$s_i = \bar{s}(n_u, n_d, m) + \frac{m-1}{A}\left[\frac{C^I}{m} - c_i\right] \tag{20}$$

where

$$\bar{s}(n_u, n_d, m) = \frac{1}{A}\left\{(m-1)\left[\frac{\beta + C^I}{m+1} - \frac{C^I}{m}\right] - \frac{B}{m}(S^I + X^{J_u})\right\}.$$

The first term is common to all the integrated firms. For a given β and a given cost vector $(c_1, c_2, \ldots, c_{n_u})$, it depends only on n_u, n_d and m. This term captures the "strategic element" in the determination of s_i. The second term on the other hand is specific to each firm. It captures the "cost differential element" in the determination of s_i.

Quite obviously, the second term can be either positive or negative, depending on whether the firm has smaller or greater than average upstream cost. For $m < n_u (\leq n_d)$, one easily verifies, by numerical examples, that $\bar{s}(n_u, n_d, m)$ may also take positive or negative values, depending on the relative values of m, n_u and n_d. Thus even if all firms had the same upstream cost, so that the second term would disappear, the integrated firms might all choose, in equilibrium, to refine more than their own upstream production by buying crude oil on the market from non-integrated upstream producers ($\bar{s}(n_u, n_d, m) < 0$). As already noted, this may seem strange at first thought, since each of them could supply itself at a cost which is lower than the equilibrium market price for crude. The reason why this may occur is that the equilibrium strategy may be one of "raising rivals' costs" (Salop and Scheffman, 1983): by buying part of their crude from the market rather than supplying themselves totally from their upstream division, they contribute to raising the cost of crude for non integrated downstream rivals and hence reduce their downstream competition.

For such a strategy to be an equilibrium one, the gains to the integrated firm from the reduced competition on the downstream market must more than offset the cost of supporting such a strategy, which is given by the upstream loss from buying the crude at a price higher than its own marginal cost of producing it. For this to occur, the number of non integrated firms must be large relative to the number of integrated firms. For if the non integrated downstream firms do not constitute a sufficiently important part of the downstream market, than the gains from the reduced downstream competition will be relatively small and will be spread across a relatively large number of integrated firms[9].

Notice that the common strategic element $\bar{s}$ may dominate the individual cost element for all i. Therefore, even though the value of s_i will vary across firms, it is theoretically possible to have s_i negative or positive for all the integrated firms, as it is possible that it be negative for some firms and positive for others.

[9] For a further discussion of this question and some examples, see Gaudet and Long (1995).

6 Conclusion

We have proposed a simple model of a partially integrated industry in order to illustrate the separate effects of strategic and of upstream cost considerations in the determination of the integrated firm's equilibrium net sales decision to the non integrated sector. The sum of the two effects for any individual integrated firm may be either negative or positive in equilibrium. Therefore a particular integrated firm's net position with respect to the upstream and downstream markets may be one of buyer or seller of the upstream good. There is however no ambiguity in the effect of upstream cost asymmetries: the integrated firm with the lower upstream cost will produce more both upstream and downstream than the one with the higher upstream cost, but its downstream production will be less important relative to its upstream production.

A casual look at the data suggests that these predictions are confirmed for the world oil industry. There is clearly room, however, for more sophisticated empirical analysis of this question. Data permitting, such an analysis might make it possible, for instance, to identify empirically the strategic and cost elements in the determination of the integrated firms' market interaction with other upstream and downstream competitors. The model could also provide a framework for an empirical analysis of other natural resource industries.

Appendix

The solution for s_i and x_j

The first-order conditions at the upstream stage are

$$\left[(p-c_i)\frac{\partial y_i}{\partial w}+y_i\frac{\partial p}{\partial w}\right]\frac{\partial w}{\partial s_i}+w+s_i\frac{\partial w}{\partial s_i}=c_i \quad \forall i\in I \tag{A–1}$$

$$w+x_j\frac{\partial w}{\partial x_j}=c_j \quad \forall j\in J_u, \tag{A–2}$$

where, from (5),(8) and (9),

$$\frac{\partial y_i}{\partial w}=\frac{\partial p}{\partial w}=\frac{n_d-m}{n_d+1}$$

and

$$\frac{\partial w}{\partial s_i}=\frac{\partial w}{\partial x_j}=-\frac{n_d+1}{(m+1)(n_d-m)}.$$

After substituting for $\partial y_i/\partial w$, $\partial p/\partial w$, $\partial w/\partial s_i$ and $\partial w/\partial x_j$, and for p, w and y_i from (8), (9) and (5), these first-order conditions can be rewritten as

$$\frac{m-1}{m+1}(\beta+C^I)+\left[\frac{2}{m+1}-\frac{n_d+1}{n_d-m}(S^I+X^{J_u})-\frac{n_d+1}{n_d-m}s_i=(m-1)c_i\right] \quad \forall i\in I \tag{A–3}$$

$$\beta+C^I-\frac{n_d+1}{n_d-m}(S^I+X^{J_u})-\frac{n_d+1}{n_d-m}x_j=(m+1)c_j \quad \forall j\in J_u \tag{A–4}$$

where $S^I=\sum_{i\in I}s_i$ and $X^{J_u}=\sum_{j\in J_u}x_j$.

Summing (A–3) over i and (A–4) over j, we find that

$$(A+B)S^I+BX^{J_u} = E \tag{A–5}$$

$$(n_u-m)AS^I+(n_u-m+1)AX^{J_u} = F \tag{A–6}$$

where

$$\begin{aligned}
A &= \frac{n_d+1}{n_d-m}\\
B &= \frac{m(n_d+1}{n_d-m}-\frac{2m}{m+1}\\
E &= \frac{m(m-1)}{m+1}\left(\beta-\frac{C^I}{m}\right)\\
F &= (n_u-m)\left(\beta-\frac{C^I}{m}\right)+(m+1)\left[\frac{n_u-m}{m}C^I-C^{J_u}\right].
\end{aligned}$$

and $C^I=\sum_{i\in I}c_i$, $C^{J_u}=\sum_{j\in J_u}c_j$. The solution of this system of two equations in S^I and

X^{J_u} yields

$$S^I = \frac{(n_u - m + 1)AE - BF}{[(n_u - m + 1)A + B]A} \tag{A–7}$$

$$X^{J_u} = \frac{(A + B)F - (n_u - m)AE}{[(n_u - m + 1)A + B]A} \tag{A–8}$$

and hence

$$S^I + X^{J_u} = \frac{E + F}{(n_u - m + 1)A + B}. \tag{A–9}$$

From (A–3) and (A–4), the solution for s_i and x_j may therefore be written

$$s_i = \frac{m-1}{A}\left[\frac{\beta + C^I}{m+1} - c_i\right] - \frac{B}{mA}(S^I + X^{J_u}), \quad i \in I \tag{A–10}$$

$$x_j = \frac{m+1}{A}\left[\frac{\beta + C^I}{m+1} - c_j\right] - (S^I + X^{J_u}), \quad j \in J_u. \tag{A–11}$$

Table 1

Output, refining capacity 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

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Figure 1

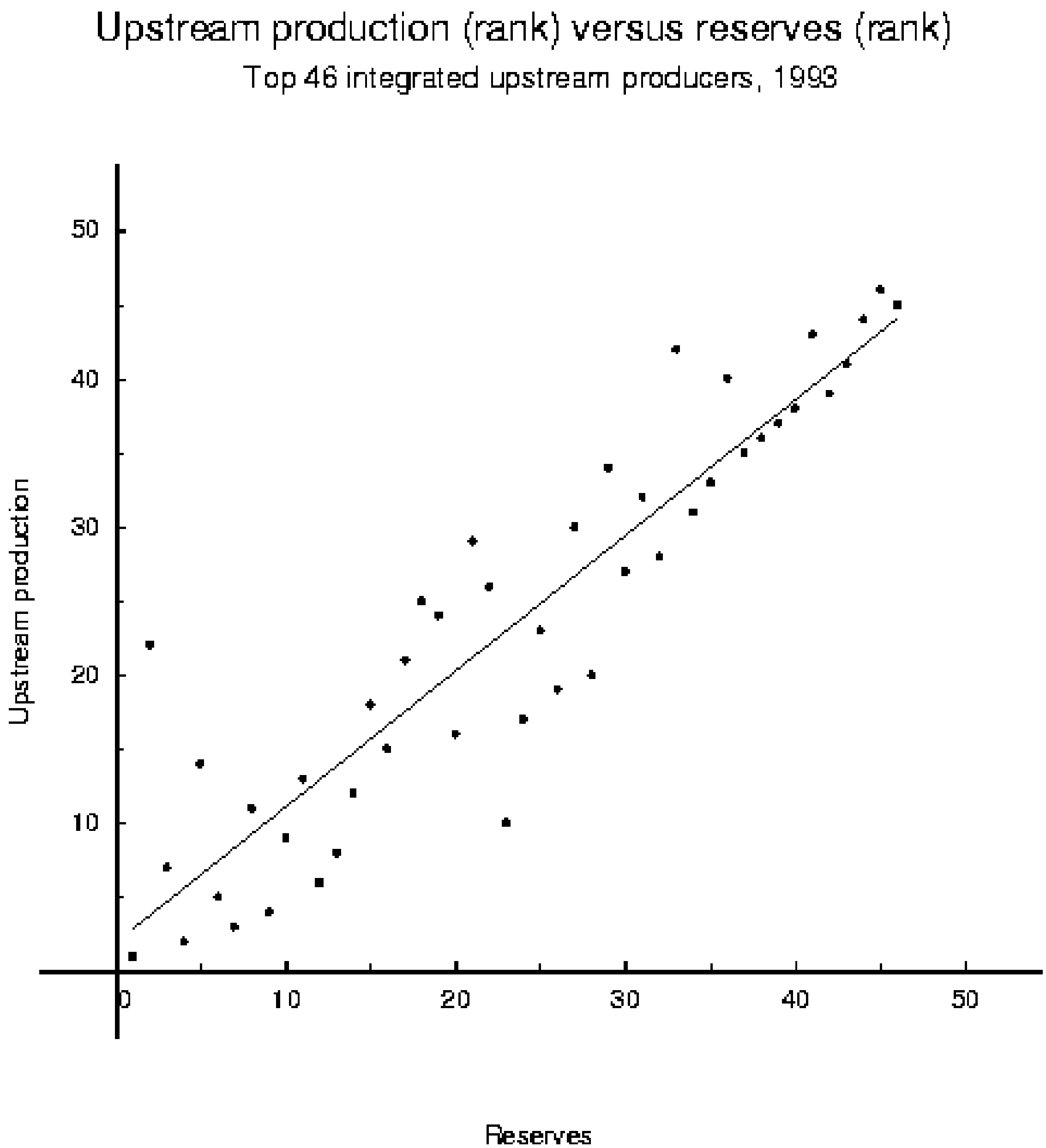

Upstream production (rank) versus reserves (rank)
Top 46 integrated upstream producers, 1993
50
40
30
20
10
0
10
20
30
40
50
Upstream production
Reserves

Figure 2

Refining capacity (rank) versus reserves (rank)

Top 46 integrated upstream producers, 1993

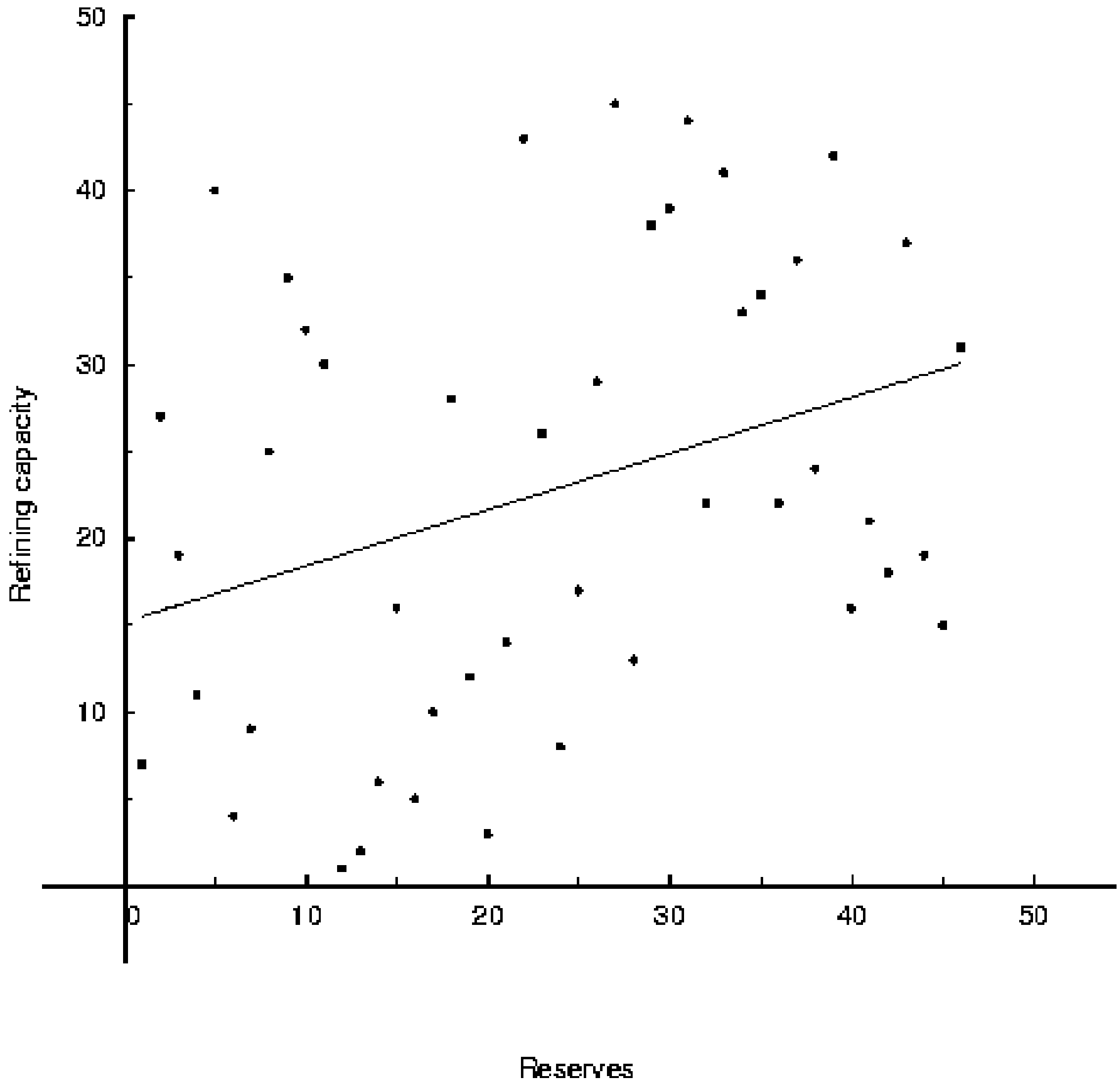
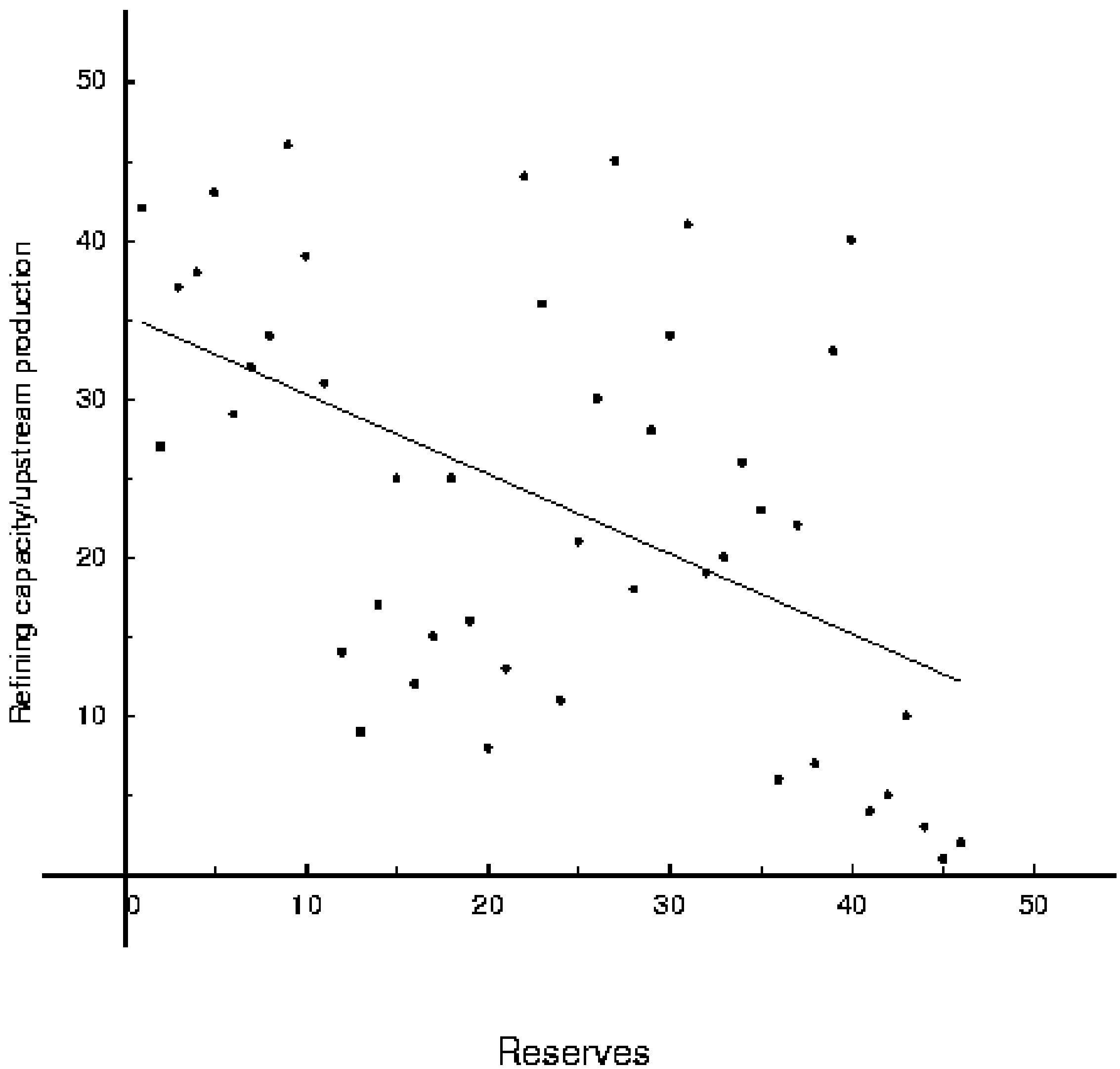


Figure 3

Refining capacity/production (rank) versus reserves (rank)

Top 46 integrated upstream producers, 1993



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